2 (mix)

CR-114854

a. 1

FINAL REPORT OF

PHASE I

STUDY PHASE

EVALUATION OF NEW APPROACHES TO PACKAGING OF POWER ASSEMBLIES FOR SPACE USE

Contract NAS 9-10411

Prepared for

NASA-MANNED SPACECRAFT CENTER
R&D PROCUREMENT BRANCH
HOUSTON, TEXAS 77058

DECEMBER 1970

ABSTRACT

An eleven-month study program was conducted by Grumman for the NASA-MSC Power Distribution and Sequencing Section to develop new approaches for the packaging of space electrical power assemblies. The Phase I Study has, as its final goal, the development of a packaging technique which will be optimum for power equipment in space environments. The packaging technique includes on-board maintenance features which will not compromise environmental integrity.

CONTENTS

CONTENTS (Cont)

CONTENTS (Cont)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont)

SECTION 1

INTRODUCTION

In an effort to reach the objective of an optimum package design for high-power electrical assemblies (1 to 50 kilowatts system size) many avenues of approach were investigated.

State-of-the-art surveys of applicable literature and available manufactured items were made. This included surveys of prior packaging approaches made for similar purposes. Compatibility of the design with on-board maintenance techniques was carefully considered.

The limitations of man working in a space environment were thoroughly surveyed, as were flexibility of application, materials for space environments, and thermal problems.

Power dissipation resulting from the inefficiencies in power conditioning circuits causes temperature increases which can affect performance and reliability of the equipments. The effects can vary from a gradual change in device characteristics and reduction in useful life to a catastrophic failure.

The trend in the component and packaging state-of-the-art is toward circuits and components handling greater electrical loads with reduced volume and weight. The designs conceived in this study resulted in power dissipation densities (i.e., watts per cubic inch) up to 30 times greater than previously experienced on the Lunar Module flight electronics.

The purpose of the study was to establish suitable design approaches utilizing current state-of-the-art technology, applying them to modularized system packaging concept with minimum electrical design restrictions, and to provide a feasible interface to future vehicle environmental control systems.

SECTION 2
STUDY OBJECTIVES

The basic objectives of the study were to develop packaging techniques, design criteria, and recommendations for follow-on study.

The packaging techniques will be applicable specifically to high-power electrical assemblies for space use. Various packaging techniques were to be evaluated and existing packaging schemes surveyed. Design layouts of high-power assemblies, representative of those in a high-capacity space power system, were to be made and trade-offs conducted in order to find the optimum packaging designs. Special attention was to be given to thermal problems, on-board maintainability techniques, materials, seals, and the limitations of man working in a space environment.

A set of design criteria, applicable to power packaging, was to be developed from the literature survey and the design layout investigations. These criteria would be suitable for inclusion in any requirement for power assemblies for space use.

The final major objective was to prepare detailed recommendations describing the best approach to follow for accomplishing the basic objective of Phase II, Design Effort and Breadboard Construction.

SECTION 3

SUMMARY

A wide literature survey was made into materials for construction and thermal interfaces, electrical and electronic packaging, maintainability, reliability, human factors, and thermal techniques. Few of the papers read contained material of direct interest.

Representative electrical power assemblies were chosen for both preliminary electrical design and mechanical packaging layout. These were:

- Power Switch Module of a 1 KW Single-Phase Inverter
- Power Transfer Module of a 1 KW DC-DC Converter
- Power Switch Module (1ϕ) of a Three-Phase Cycloconverter

These units were chosen for investigation because they are representative in size, thermal dissipation, and other problem areas with almost any unit likely to be met in a 25 to 50 KW power conditioning and distribution system. Thermal and electrical analyses have been made of these packaging approaches, and it has been determined that the approaches are optimum for the purpose intended.

A list of design criteria, extracted from the study designs and trade-offs and from the literature search, is in a format readily useable to define specifications for space flight items.

Recommendations are made for further development of the study into Phase II, Design Effort and Breadboard Construction.

SECTION 4

GROUND RULES AND ASSUMPTIONS

The ground rules governing the design approaches are:

- Normal operating ambient is to be $70^{\circ}F$, 14.7 psia or less air/oxygen (shirt sleeve environment) with the capability to operate at the same temperature in a space vacuum.
- All module surfaces are to remain within a crew touch criteria of $120^{\circ}F$ maximum. The entire thermal design must operate both in a zero gravity and in artificial gravity in a known "g" direction
- An active coolout loop at $90^{\circ}F$ maximum is assumed as the required heat rejection system.
- Designs must permit maintainability in a vacuum environment.
- No coolant lines are to be parted for module removal.
- Design for minimum box-to-coolant interface configurations and maximum form factor standardization.
- Minimum weight on an overall systems basis must be considered.
- Replacement/removal of modules performed by one crewman using one hand, if possible.
- The use of tools will be minimized.
- Replaceability will be at the module level only.
- Power assemblies investigated must be typical of those likely to be found in an actual space vehicle power system of 1 to 50 KW size.
- Environmental integrity must not be compromised by maintenance features.

- The maximum acceptable solid-state component junction temperature is $100^{\circ}C$, with other component surface temperatures limited to $82^{\circ}C$ under all extremes of operating conditions.
- Temperature drops and thermal resistances are to be minimized wherever possible, particularly at the interfaces of component plates with module enclosures and at module flanges with coolant loops.
- The proposed internal thermal design must be readily adaptable to less severe power dissipation conditions.

SECTION 5

LITERATURE SEARCH AND DISCUSSION

An extensive literature search was conducted to obtain background material as well as information directly applicable to the study. Areas of interest included existing packaging systems and their compatability with study design problems, heat pipes and thermal control, maintainability and reliability, human factors, latching mechanisms, and design criteria. Special emphasis, in the form of a separate literature search, was given to thermal interfaces, structural materials, and electrical/electronic packaging systems.

Numerous papers were reviewed, but few contained material of direct value to the study. The majority of the technical reports are concerned with relatively low-dissipation electronic assemblies (25W or lower) rather than high-dissipation power conditioning assemblies. In addition, many of the papers were not concerned with space environments and, therefore, have limited applicability. Several interesting reports describing the operation and application of heat pipes as a means of transferring large quantities of heat with small temperature differences were obtained.

5.1 STRUCTURAL MATERIALS

Throughout the development of the equipment rack and module designs, consideration was given to fabrication techniques; thus, the designs developed require a minimum of machining and, therefore, should be relatively simple and inexpensive to manufacture. The equipment rack assembly can be fabricated almost entirely of extrusions. The cold rails, however, require close-tolerance machining on the mounting surface to insure proper surface finish and flatness. The standard module case configuration as used in the DC-DC Converter Power Transfer Module, Figure 5-1, can be cast with only areas such as the mounting flanges requiring machining. The chassis of the Cycloconverter module, Figure 5-2, is an extrusion with close tolerance machining on the chassis-to-cold plate mounting surface and with local spot-facing of the flanges to mount the silicon-controlled rectifiers (SCRs). In choosing materials, consideration was given to the material properties and available forms.

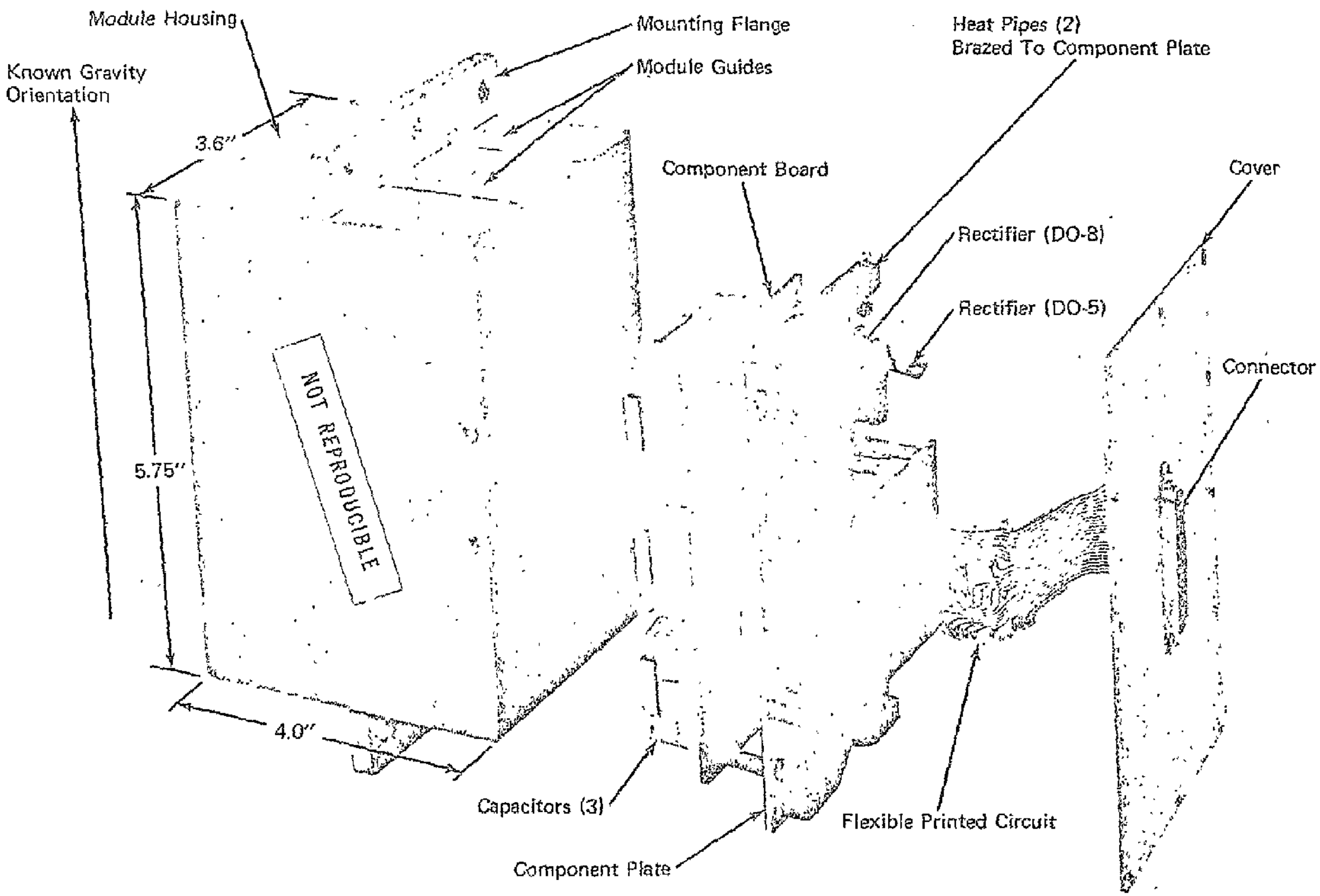


Figure 5-1. 1 KW POWER TRANSFER MODULE (DC-DC CONVERTER), EXPLODED VIEW

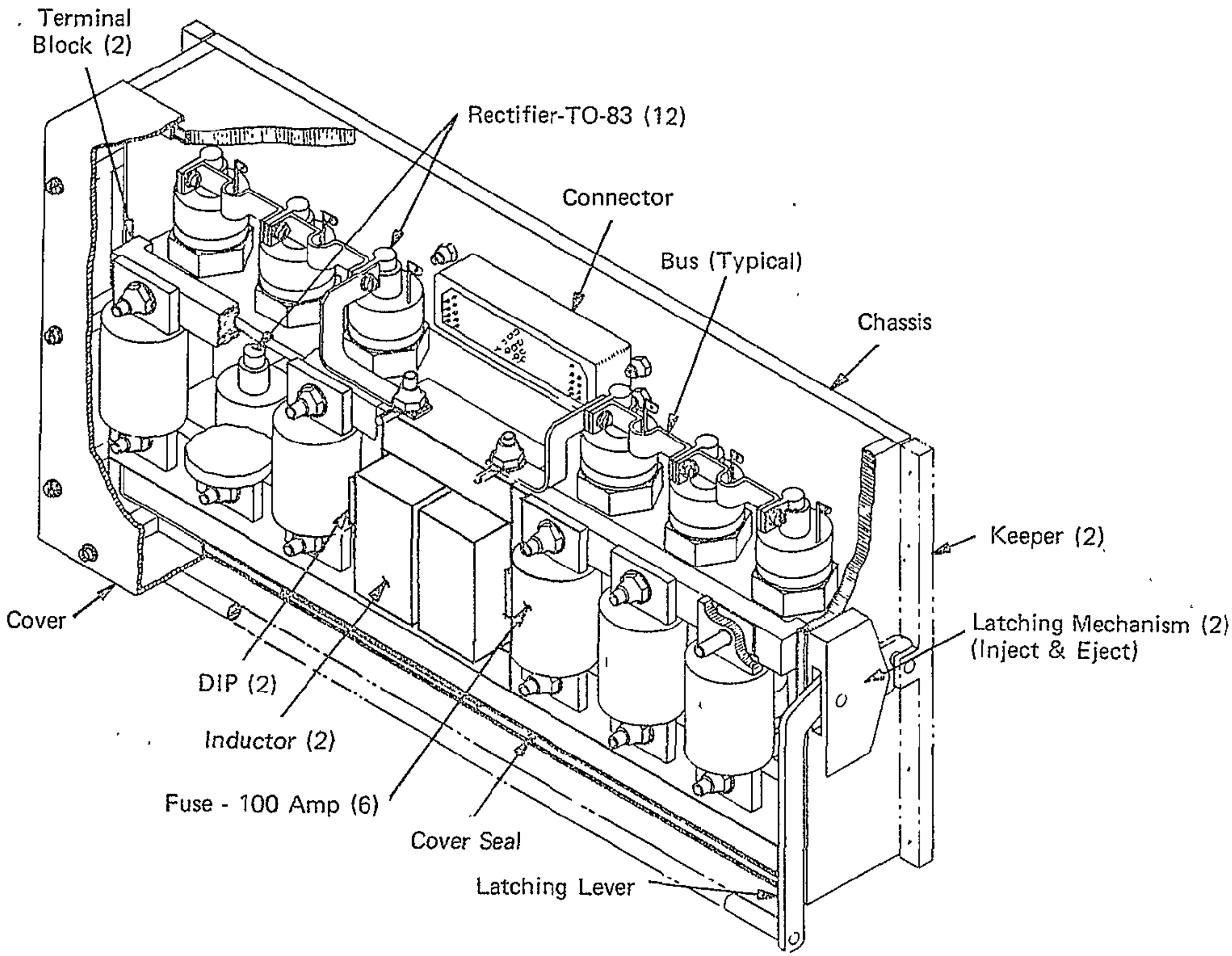


Figure 5-2. CYCLOCONVERTER POWER SWITCH MODULE
(SINGLE PHASE CHANNEL)

Three groups of materials were considered: beryllium and Lockalloy (Be- 38% Al), the magnesium-base alloys, and the aluminum-base alloys. The evaluation was based on structural, thermal, and fabrication characteristics. Consideration also was given to corrosion resistance, potential safety problems associated with a material's use, and compatability with other materials.

The use of beryllium and Lockalloy is not recommended for this specific application. Although these materials offer the highest strength-to-density and thermal conductivity-to-density ratios of all materials surveyed, they possess several significant drawbacks.

Discussion

Beryllium is a high strength, low density structural material that has had limited use in spacecraft. It has the highest strength-to-density ratio of all the materials considered and, in addition, offers a thermal conductivity-to-density ratio second only to the beryllium-aluminum alloy, Lockalloy. Beryllium is available in vacuum hot-pressed blocks, cross-rolled sheets, plates, wire, extrusions, and forgings. Commerically pure beryllium is difficult to cast into sound ingots. The castings have large grains and are not suitable for structural use. Under normal service conditions, a tough stable oxide coating (about 100 Å) protects beryllium from corrosion. Extreme pH conditions will cause the protective oxide coating to dissolve and form salts and beryllates. Galvanic corrosion can be a severe problem with beryllium, and coupling beryllium with more noble metals, especially the stainless steels, should be avoided. In addition, the inhalation of beryllium particles can cause berylliosis, a chronic lung disease. Beryllium, therefore, must be machined in a controlled environment and should not be used within spacecraft crew compartments unless suitably protected to prevent erosion or the formation of salts or oxides.

Lockalloy is a beryllium-aluminum alloy which as been developed to compromise the ductile properties of aluminum with the high strength properties of beryllium. Although its strength-to-density ratio is 28% lower than that of pure beryllium, Lockalloy exhibits the highest thermal conductivity-to-density ratio of all materials evaluated. The addition of aluminum has resulted in a material with substantially improved machining, forming, and welding characteristics. The corrosion resistance of the alloy has not been fully determined. The available forms include rods, bars, and sheets in limited sizes. Lockalloy castings are not yet available. The high beryllium content of Lockalloy requires that the same health restrictions be imposed on its fabrication and application as those placed on pure beryllium.

The limited availability of forms and sizes of beryllium and Lockalloy, the inability to cast these materials, the safety hazard accompanying their use, and the comparative high cost involved are substantial reasons why these materials are not considered appropriate for first choice for rack and module fabrication. The properties of Lockalloy are such, however, that it possesses great potential and eventually may be considered applicable in future designs.

The magnesium-base alloys offer several alternative materials for rack and module construction. Both wrought and casting alloys, in virtually all forms and sizes, are available. Magnesium alloys possess lower yield strengths and thermal conductivities than beryllium, Lockalloy, or the aluminum-base alloys but, due to their low densities, they have strength-to-density and thermal conductivity ratios comparable to most aluminum-base alloys. The machinability of magnesium alloys is excellent and most alloys are readily weldable. In addition, magnesium alloys possess an energy absorbing characteristic useful for vibration damping. These alloys are slightly softer than aluminum alloys. As discussed above, this should give magnesium alloys an advantage over aluminum alloys in interface thermal conductance. The most significant drawback of these alloys is their relatively poor corrosion resistance, which is somewhat less than that of aluminum. Some type of additional corrosion protection in the form of a coating system is often necessary. In addition, magnesium is a very active metal with an electromotive potential of -1.60 volts, which places it at the anodic end of the galvanic series. Consequently, magnesium can suffer accelerated attack when coupled, in the presence of an electrolyte, to most metals below it in the galvanic series. Preferably, therefore, magnesium alloys should be coupled only to themselves, other magnesium alloys, or the permissible aluminum alloys 5052, 5056, 5356, 6061, and 6063. A detailed discussion of methods of corrosion protection is provided in Reference 1 along with the coating properties. The properties of several magnesium alloys are given in Table 5-1. Based on the data accumulated during this study, these alloys offer properties most desirable of materials in their group. These alloys

MATERIAL	TYPE	ALLOY	DENSITY, Lb/In.^{3}	YIELD STRENGTH, KSI	THERMAL COND (K), Btu-Ft/Hr-Ft
Magnesium	Casting	QE22A (T6 Cond)	.066	23.0	65.34 (@68°F)
		ZH62A (T5 Cond)	.0675	22.0	63.0 (@68°F)
	Wrought	HM21A	.0642	21.0	79.2 (@ R.T.)
		HM31A	.0651	26.0	60.5
Aluminum	Casting	A356	.097	30.0	87.0
		355 (T6 Cond)	.098	25.0	82.0
	Wrought	6061 (T6 Cond)	.098	35.0	96.7
		7075 (T73 Cond)	.101	55.0	90.0
		6101 (T6 Cond)	.098	28.0	125.8

TABLE 5-1

ATERIAL PROPERTY DATA

AL K), -Ft^2-°F	THERMAL EXP COEF, In./In.-°F	YIELD STR DENSITY, x 10^3 In.	THERMAL COND DENSITY, Btu-In.^{3}/Lb-Hr-Ft^2-°F	MACHIN-ABILITY	WELD-ABILITY	MAX USEABLE TEMP, °F
	14.5 (68-212°F)	348.5	990.0	Very Good	Fair	400
	15.1 (68-392°F)	325.9	933.3	Very Good	Good	300
	14.5 (@200°F)	327.1	1233.6	Excellent	Good	700
	13.6 (0-200°F)	399.4	929.3	Good	Good	900
	11.8 (@200°F)	309.3	896.9	Fair	Good	400 (If Heat-Treated)
	12.35 (@200°F)	255.1	836.7	Good	Good	300
	13.0 (@200°F)	357.1	986.7	Fair	Excellent	300
	13.2 (@200°F)	544.6	891.0	Good	Not Weldable	225
	13.0 (68-212°F)	285.9	1282.0	Fair	Good	-

should be used where thermal considerations are of prime importance and the danger of corrosion is minimal.

The magnesium-based alloys offer the best material properties for the fabrication of equipment developed in this design study and therefore are recommended for use. Both cast and wrougth alloys with excellent machining characteristics are available. From a thermal standpoint, magnesium alloys offer higher thermal conductivity-to-density ratios than most aluminum alloys and provide greater interface heat transfer than a comparable aluminum interface. The only significant drawback to their use is their relatively poor corrosion resistance. For many applications, magnesium alloys must be protected against corrosion. This is not considered a problem in this application since suitable corrosion prevention techniques are available.

Aluminum-based alloys should be used where increased strength and corrosion resistance is required. Their use in place of magnesium alloys generally will compromise thermal aspects of a design. A few aluminum alloys are available with thermal characteristics comparable to magnesium alloys; however, these alloys possess lower structural strength. The fabrication characteristics and availability of these alloys are similar to those of the magnesium alloys.

Several aluminum alloys possess favorable properties for module and rack fabrication. Aluminum alloys have a higher density and slightly lower thermal expansion coefficient that magnesium alloys and possess comparable machinability and weldability. Alloys with excellent casting characteristics are available. Heat treatment of aluminum alloys can result in strength-to-density ratios comparable to magnesium alloys and, in some cases, exceeding that of Lockalloy. These high-strength alloys generally are not as corrosion-resistant as the high purity or moderate strength aluminum alloys but are considered satisfactory. Excellent resistance to corrosion is made possible by the protective, highly adherent oxide film which develops in air, oxygen, or oxidizing media. Being less anodic than magnesium alloys, aluminum alloys offer greater resistance to galvanic corrosion and therefore can be safely interfaced to a greater variety of dissimilar metals. Table 5-1 provides materials property data for aluminum alloys considered applicable to the packaging design. The data given in Table 5-1 was obtained from Reference 2.

One alloy of particular interest due to its high thermal conductivity is 6101 aluminum. This material is widely used for electrically conductive busbars and motor components, and possesses reasonably good mechanical strength and material properties. Its use, however, may be limited by availability in the forms and sizes compatible with module and rack designs. A special extrusion die can be procured, if required.

In general, aluminum alloys should be used where material strength and corrosion resistance is of prime importance. The 6101 alloy may be used where high thermal conductivity is essential and desired forms are available.

The materials noted in Table 5-1 are those which appear to have properties most desirable for fabrication of racks and modules. These are by no means the only materials that can be used and are considered only as favorable candidates. Prior to any final selection, additional information and data must be obtained. Reference 2 is an excellent up-to-date source of metallic materials. Information about non-metallic materials (plastics, polymers, ceramics, ceramoplastics, and glasses) may be obtained from Reference 3.

5.2 THERMAL INTERFACE MATERIALS

The problem of poor heat transfer across an interface arises as a result of incomplete surface contact due to surface irregularities and flatness deviations. This situation is aggravated in a vacuum as heat is required to flow through interface voids by radiation only. To improve heat flow, it is necessary to maximize the effective surface contact area through improved surface finish and flatness. The use of softer joint materials, increased contact pressure, and the introduction of interface materials to fill the interface voids also can improve heat transfer.

Based on the information gathered, it appears that unloaded silicone greases are the best currently available interface materials. They provide high interface conductivity, are less sensitive than rigid materials to contact pressure variations caused by poor finish and flatness deviations, and allow easy interface separation while presenting no handling problems in a shirt-sleeve environment. Under a suited condition, the handling of silicone greases may present some problems, but the handling of other interface materials - foils and silastics - also could present difficulties. Indium foil can be used as an alternative interface material, provided that a fastener could be developed that will supply uniform and sufficient contact pressure and that surface finishes and flatness deviations are carefully controlled.

The effect of surface finish and contact pressure on interface conductance is evident from Figure 5-3 (Reference 18), which is a plot of contact conductance vs contact pressure for aluminum specimens of varying surface finish in air. As can be expected, decreasing the surface roughness or increasing contact pressure causes a substantial increase in the joint conductances. Figure 5-4 (Reference 18) illustrates the results of a series of tests with bare specimens of varying surface finish and flatness in a vacuum. As depicted, the vacuum environment substantially reduces the interface conductance. Surface flatness has a major effect on contact conductance; consequently, the specimen with the finest surface finish exhibited the lowest contact conductance due to its large flatness deviation. It is also apparent that, at contact pressures above seven psi, the magnesium specimen provided the highest contact conductance even though surface roughness and flatness deviations were greater than those of two of the aluminum specimens. This is attributed to the comparatively softer magnesium specimens (Rockwell B hardness: Mg = 72, Al = 77). It was determined that surface asperities deformed to a greater extent in the softer material, causing a corresponding increase in effective contact area.

The introduction of an interface material in a vacuum situation can substantially increase the heat transfer through an interface. Experimental evidence has shown that the joint thermal conductance can vary greatly with the interface material used. Figure 5-5 (Reference 18) illustrates the results of some tests performed with metallic interface materials. The aluminum specimens used with the lead foil were those having a surface finish of 6-8 micro-inches (rms) and a flatness deviation of .0045 inch. A large increase in conductance over that of the bare joint was exhibited. These same specimens were used to test a copper wire cloth interface. At contact pressures above approximately seven psi, the conductance of the bare joint exceeded that of the joint with the copper wire cloth. Aluminum foil was the interface material for another test using specimens of 48-65 micro-inch (rms) surface finish and .0017 inch flatness deviation. Some improvement over the corresponding bare joint (Figure 5-4) is noted, but the improvement was not as great as that with the lead foil interface. Several other interface materials were

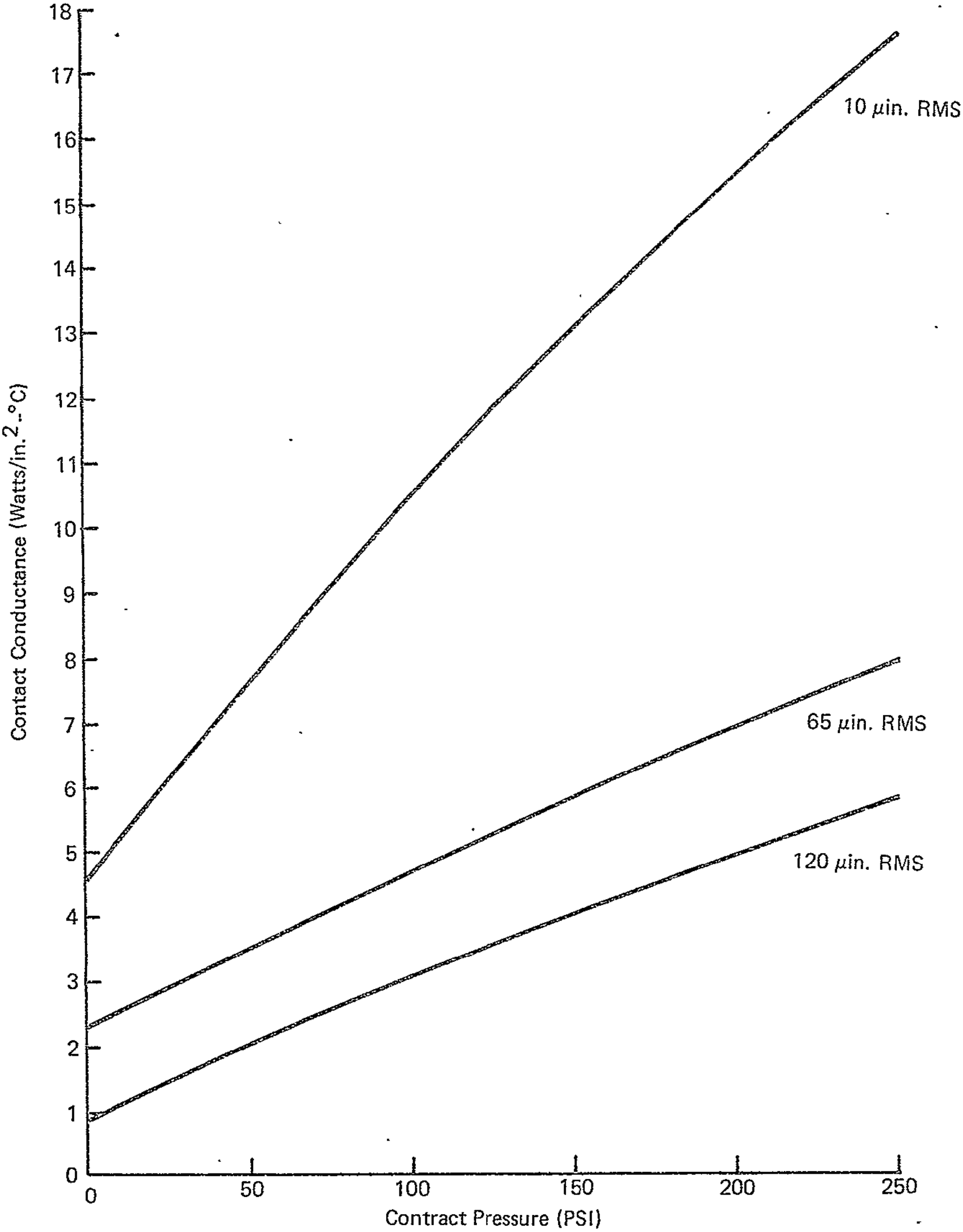


Figure 5-3. THERMAL CONTACT CONDUCTANCE OF ALUMINUM INTERFACES IN AIR VS. CONTACT PRESSURE

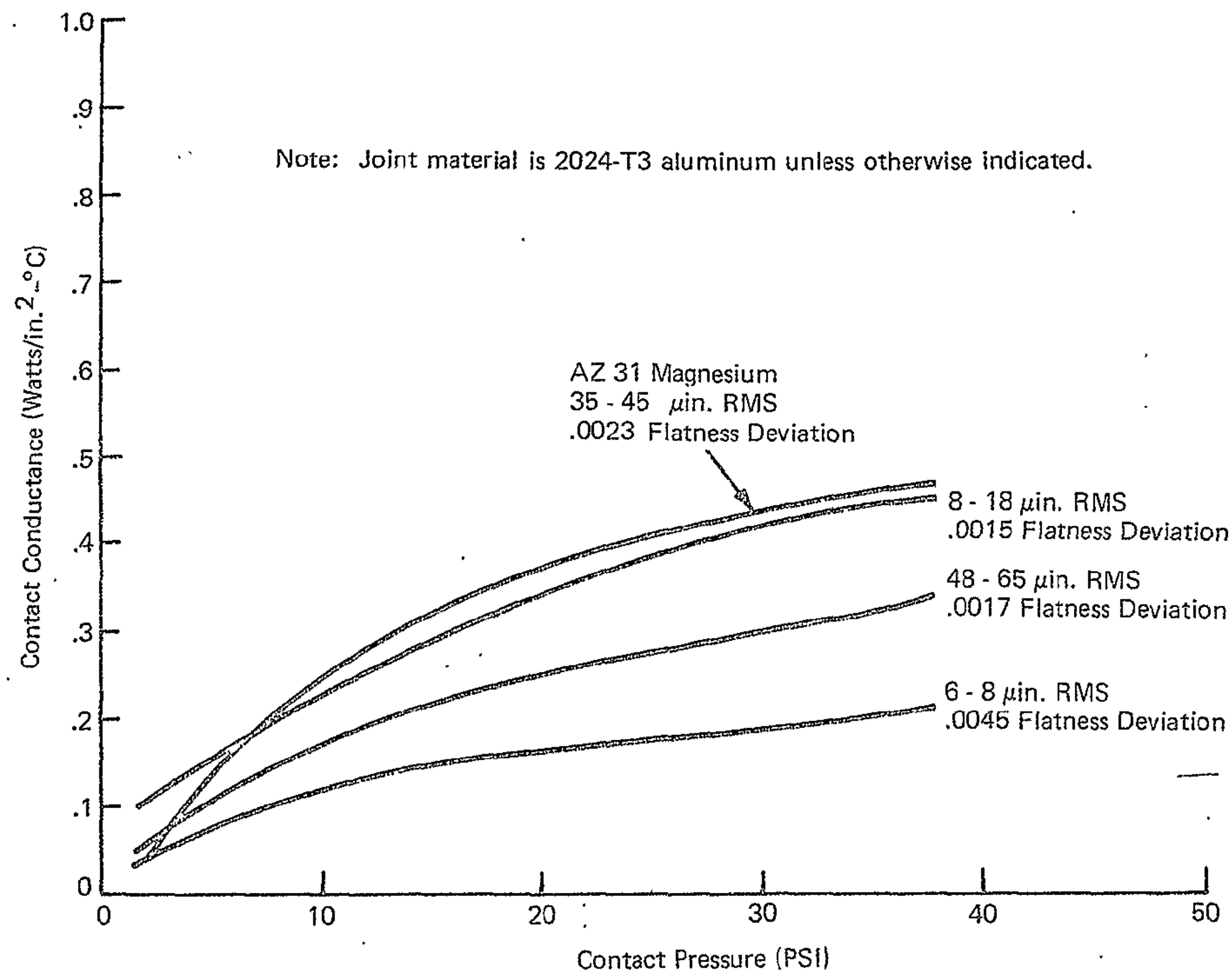


Figure 5-4. THERMAL CONTACT CONDUCTANCE OF BARE JOINTS IN A VACUUM VS. CONTACT PRESSURE

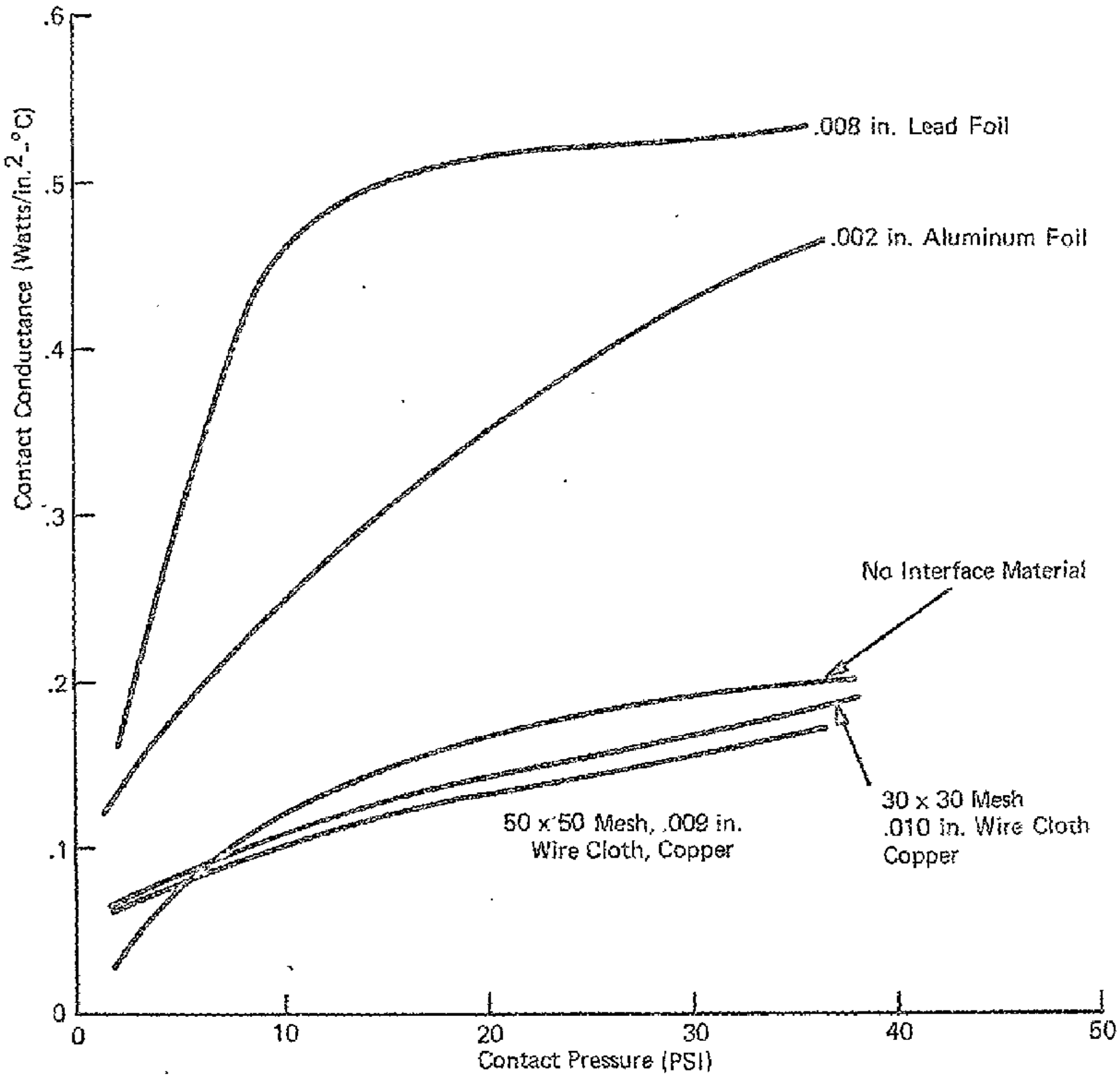


Figure 5-5. THERMAL CONTACT CONDUCTANCE OF ALUMINUM JOINTS WITH INTERFACE MATERIALS IN A VACUUM VS. CONTACT PRESSURE

compared in a different testing program that used aluminum specimens of 125 micro-inch (rms) finish and undetermined flatness deviation. The results are given in Figure 5-6 (Reference 19). While the numerical values cannot be compared to those of Figures 5-3, 5-4, and 5-5 due to differences in test setups, results similar to those of Figure 5-5 are evident.

Based on the results indicated in Figures 5-5 and 5-6, it appears that the effectiveness of an interface material is more dependent on material hardness than thermal conductivity. The softer interface materials more readily fill the interstitial voids and, therefore, provide a larger effective area for conduction. The use of soft-type base materials, fine finishes, and reasonable pressures are indicated for future design development.

The investigation was extended to non-metallic interface materials. Materials that have been tested include a room temperature vulcanizing (RTV) silicone rubber between surfaces of 6-8 micro-inches and 150 micro-inches (rms) and a silicone grease (G. E. XS4073) between specimens with 40 and 180 micro-inch (rms) surface finishes. The results are indicated in Figure 5-7 (Reference 20). Good results were indicated with the silicone grease for the entire range of contact pressures. Conductance values for the grease are higher than those for the lead foil for all contact pressures, with a marked improvement at contact pressures below ten psi. Wiping the grease from the joint surfaces reduced the interface thickness and further improved the conductivity of the joint. Cleaning the surfaces with alcohol and testing the "bare" joint gave results comparable to specimens with surface finishes of 8-18 micro-inches (rms), as seen in Figure 5-4. This is probably the result of residual grease impregnating the specimens. The surface tension of the silicone oils, which are the base of silicone greases, is such that they readily "wet" metal surfaces but cannot be removed readily by wiping.

Some improvement to greases can be achieved by adding metallic powders. The advantages of using a filled silicone grease are evident from Figure 5-8 (Reference 4). A drawing of the test set-up is shown in Figure 5-9 (Reference 4). The interface temperature drop using the grease was less than $2^{\circ}F$ and was nearly constant along the entire length of the module flanges.

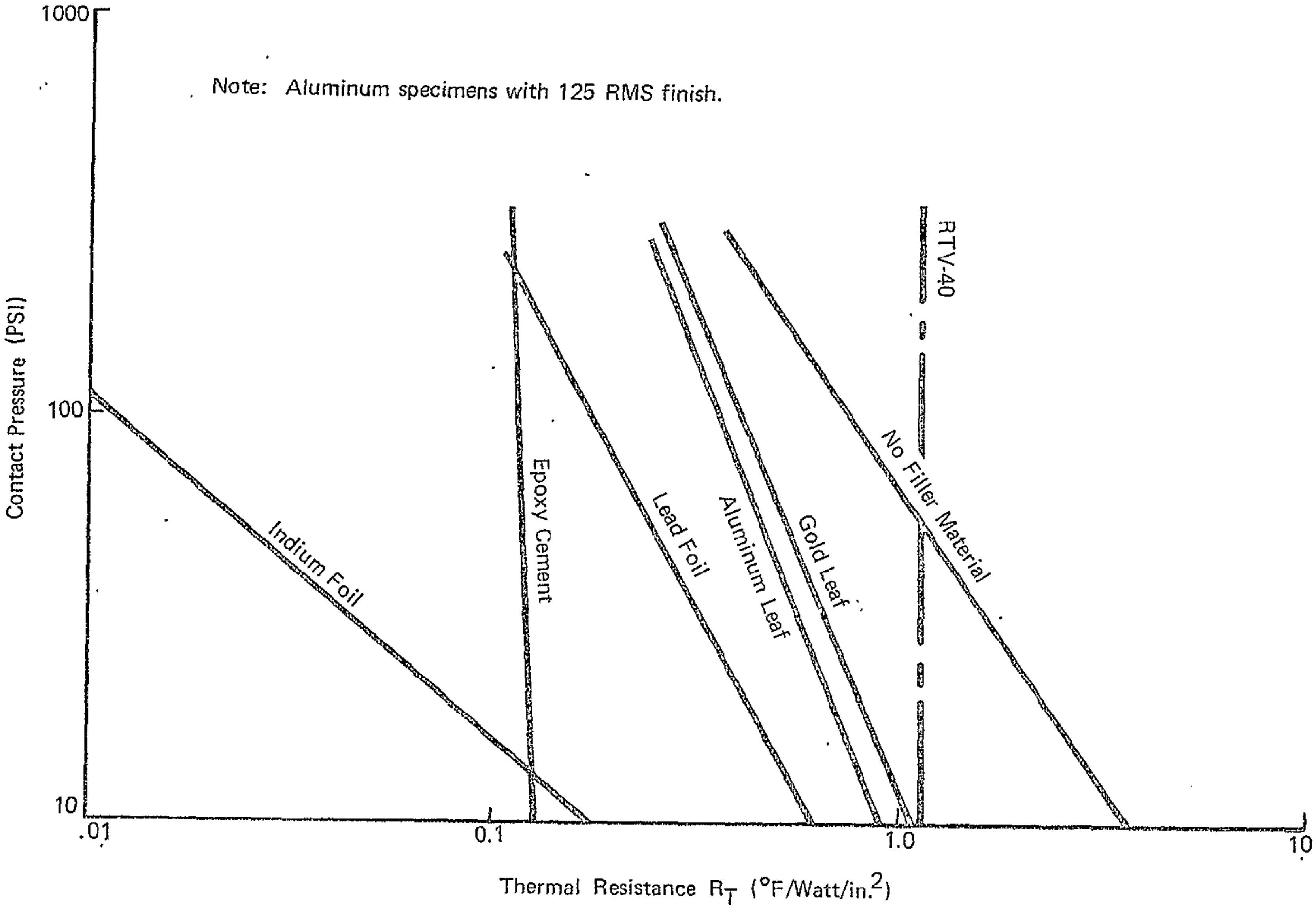


Figure 5-6. LM DATA: THERMAL RESISTANCE OF METALLIC INTERFACE WITH VARIOUS FILLER MATERIALS

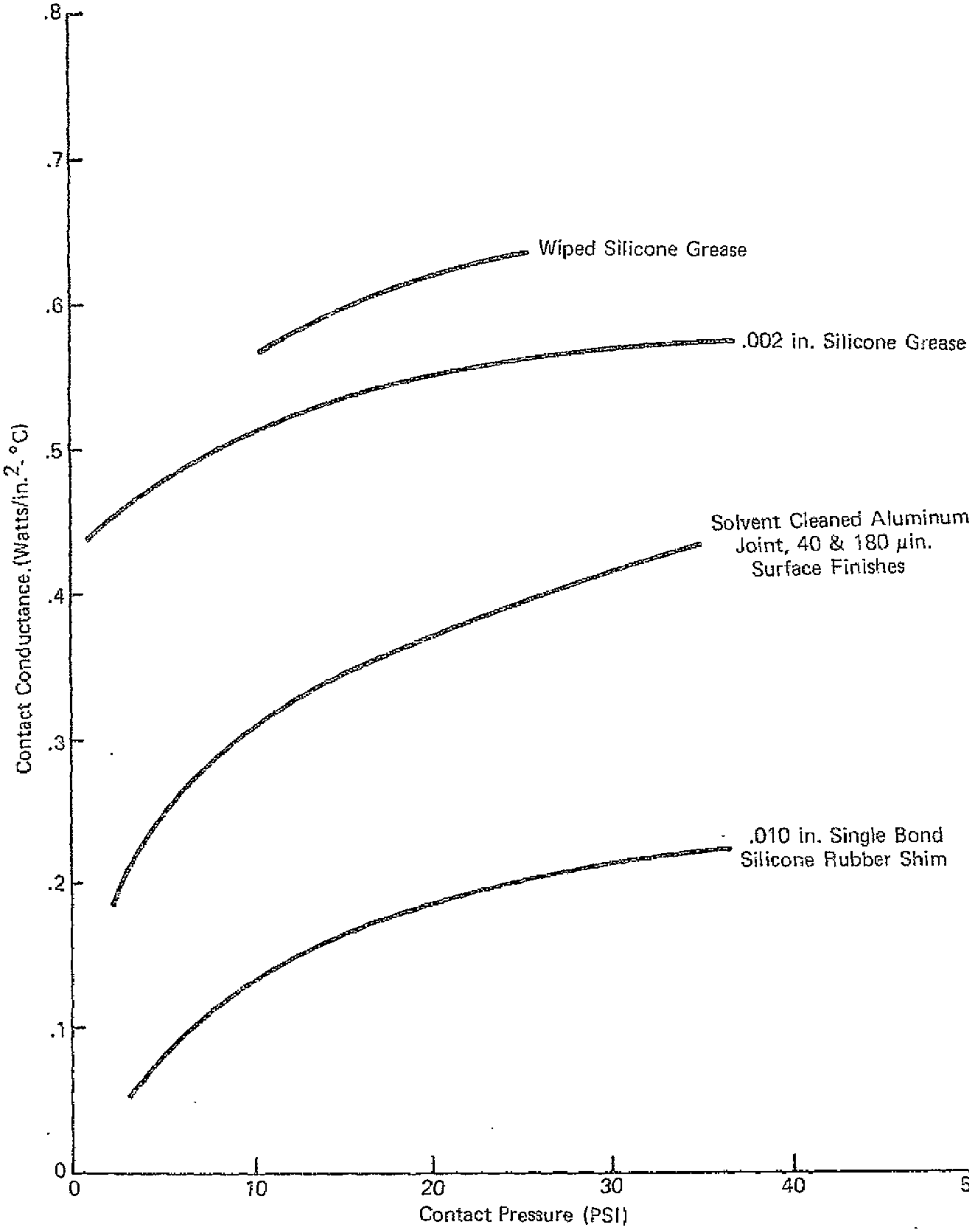


Figure 5-7. THERMAL CONTACT CONDUCTANCE OF NON-METALLIC INTERFACE MATERIALS IN A VACUUM VS. CONTACT PRESSURE

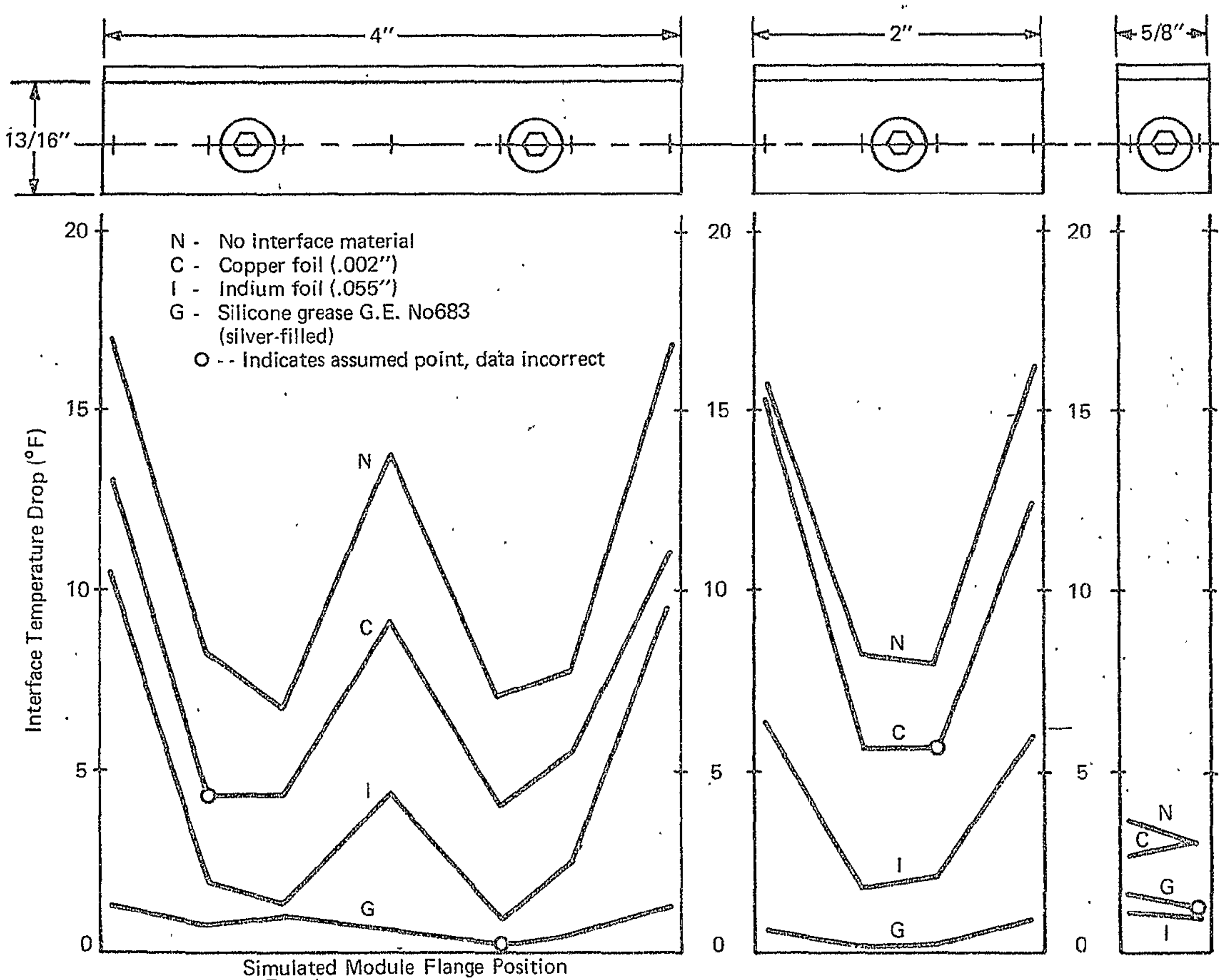


Figure 5-8. INTERFACE TEMPERATURE DROP VS. MODULE FLANGE POSITION WITH VARIOUS INTERFACE MATERIALS

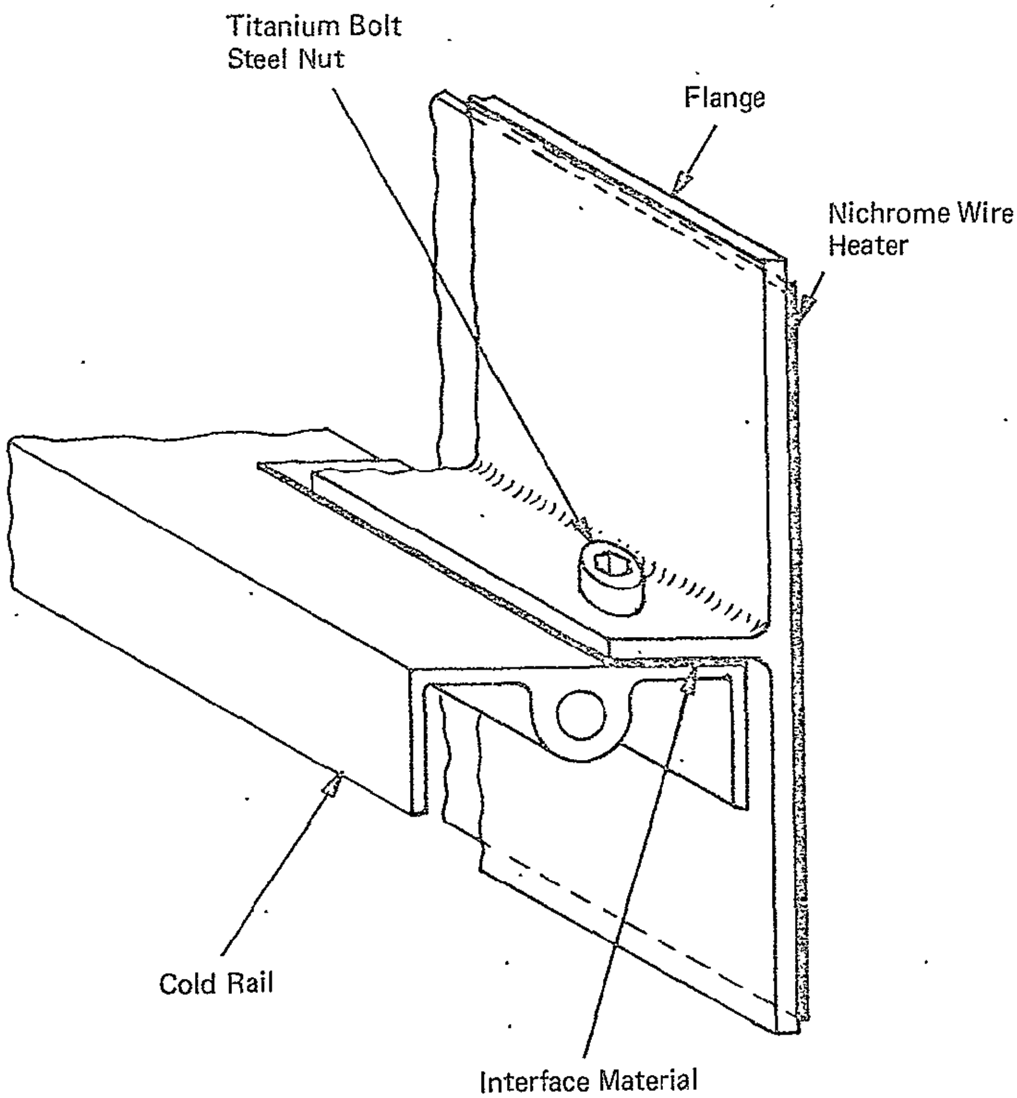


Figure 5-9. FLANGE–COLD RAIL ASSEMBLY

A possible drawback with the use of a filled grease is that the conductive filler materials could contaminate the atmosphere or migrate to areas where it might cause an electrical malfunction. Since the unfilled grease exhibits the same relatively constant interface conductivity as the filled grease (Figure 5-8) but at a slightly lower value than the filled grease, it is the recommended approach for vacuum situations.

One approach for the control of silicone grease migration is the application of a barrier material, that is, a material which silicone oils will not wet. William F. Nye, Inc. of New Bedford, Massachusetts has developed a barrier material called Nye Bar. This can be applied via brushing, spraying, or dipping and can be used at elevated temperatures. Maximum useable temperature is a function not so much of film stability as of the relative surface tensions of the oils being controlled. Surface tensions of fluids decrease as temperatures rise.

Near $400^{\circ}F$, the surface tensions of silicone oils will become sufficiently low that the film will no longer restrain them. There is also a maximum quantity of oil which the film will restrain. Gravity or dynamic forces can cause large quantities of oil to literally overwhelm the barrier film. Since the barrier material is relatively new and has had limited use, characteristics such as outgassing rates have not been investigated.

Outgassing of greases is not considered a problem where a pressurized environment is provided. For applications in a low pressure or vacuum environment Dow Corning 340 silicone grease could be used. This grease has been approved for the Lunar Module (five psia, 100% O_2) as referenced in Grumman Specification #LSM-14-6006 dated 19 July 1966.

In high pressure fastener areas, indium foil provides a good alternative to silicone greases. At positions not in the vicinity of the fasteners, the interface conductivity decreases rapidly, indicating poor conformity and a lack of intimate surface contact. The design of a fastener which would result in a uniform interface contact pressure would greatly increase the effectiveness of foils as interface materials. Such a fastener could result in an indium foil interface comparable to that available with silicone greases.

The results above were further substantiated by a series of tests conducted for the Lunar Module (LM) program by the Grumman Thermal Laboratory, Reference 4.

5.3 PACKAGING SYSTEMS

References 5, 6, and 7 discuss several existing packaging systems. Each packaging approach has several points of interest, but the basic requirements of each make them unsuitable for high-power assemblies in space.

The NAFI (Naval Avionics Facility, Indianapolis) system is an attempt to standardize mechanical and electrical interfaces. Standard electrical functions are packaged in a limited number of basic module sizes. The modules accept the necessary microelectronic and discrete components. These modules (amplifiers, flip-flops, etc.) are useable on any system. They are mounted to a base-plane wiring assembly which adapts to standard racks. The entire rack assembly is air-cooled.

Another packaging system was used by General Electric Missiles and Space Division for the PCM Multicoder. The basic electronic module uses thin film hybrid circuits mounted to two printed circuit boards secured in a magnesium frame. The modules are then mounted to a point-to-point wired chassis. The system exhibits excellent vibration and shock resistance and is conduction-cooled.

Lockheed Missile and Space Company has developed the Universal Component Packaging System. Integrated or thin film circuits and discrete components are assembled to two planar circuit boards which are mounted in an aluminum frame module. These modules are mounted on a mother board and are enclosed in a container which has environmental sealing capabilities. The modules are conduction-cooled.

The Naval Research Laboratory has developed the Centralized Electronic Control System (CECS). This accepts both conventional and microelectronic circuitry. These mount to variable-size modules with common electrical and mechanical interfaces. The modules fit into slide-out racks which interface with the enclosure. The system uses combined air and liquid cooling.

Teledyne Systems, Inc. has developed the Integrated Helicopter Avionic System (IHAS). This design for digital airborne equipment uses microelectronic modular assemblies mounted in a conduction and forced air-cooled chassis assembly.

The Naval Electronics Laboratory's Integrated Packaging System uses microelectronics or conventional circuitry in a single interface installation. Single or double racks or drawer enclosures are available options. The enclosures are centrally or individually air-cooled.

The Grumman proposed packaging system is discussed and compared to these in Section 6.1.

SECTION 6

DEVELOPMENT OF DESIGN APPROACHES

6.1 MECHANICAL DESIGN AND PACKAGING

Salient features of the Grumman packaging system are:

- Designed primarily for high-dissipation equipment, but equally applicable to lower power dissipation equipment as well
- Standardized module configurations, both externally and, where possible, internally
- Variable module size (in standard increments)
- The electrical interface with mother board connectors is an integral part of the module
- Structural and thermal interface to standardized cold rails and cold plates
- Equipment rack is standard size
- Quick-release, captive fasteners are used to mount modules—
- Electronic components are replaceable within the module (if required)

The system being developed for the packaging of power assemblies for space environment provides high reliability and maintainability. This is accomplished through the use of standardized modules mounted to equipment racks. Should a failure occur, these modules are readily replaceable and can be repaired in a properly equipped space laboratory. Thus, a minimum number of spare modules are necessary for a mission. Both the size and weight of individual modules has been kept to a range of values that readily can be handled by one astronaut in a zero to 1 g environment. Modules are held in place by quick-turn fasteners at appropriate locations. These fasteners are necessary to maintain an efficient module-to-cold rail thermal interface. A quick-release mechanism has been incorporated into large modules. This mechanism should greatly reduce module replacement times. The adaptability of a similar mechanism to smaller modules, which would greatly increase maintainability, is being considered.

Internally, an attempt has been made to develop circuit layouts that are readily repairable and thermally balanced. Through proper thermal design and the use of heat pipes, the module reliability can be high. Special emphasis has been given to the maintenance of proper thermal interfaces both internal and external to the modules. Where dissipations are beyond the capacity of cold-rail cooling, a cold plate cooled module has been developed. The cold plate and module are easily incorporated into the standard rack design.

The system described has several advantages over each of the existing systems summarized. These advantages are as follows:

- It is designed for high/low dissipation in electrical or electronic equipment, whereas the other systems mentioned are designed principally for electronics only.
- It uses conduction cooling-to-closed loop liquid cooling. The NAFI, Centralized Electronic Control System, Integrated Helicopter Avionic System, and Integrated Packaging System all use air cooling entirely or partially and, therefore, are not applicable to a space environment.
- Thermal interfaces are permanent. Only the interface of the module being replaced is broken. Drawer enclosures used in the Centralized Electronic Cooling System and the Integrated Packing System require the thermal interface of the entire drawer to be disconnected for replacement of any single module. Re-establishment of the proper thermal interface may be difficult.
- A weight savings over the slide-out tray arrangement is probably realized. The slide-out tray or drawer requires that two latching mechanisms be used, one for the module in the drawer and the other to lock the drawer in place. The slide mechanism and drawer construction also adds additional weight to the system.

The first packaging design study undertaken was that of a 1 Kw Single Phase Inverter. This unit consists of seven plug-in modules, a connector plate, and a mother board (Figure 6-1). Five of the modules - Reference Voltage Detector Amplifier, Reference Oscillator, Programming, Bias Supply, and Power Drive - are basic single-thickness modules. The Power Switch and the Filter are multiple-thickness modules.

The basic module configuration is a single-thickness module increment which is illustrated in Figure 6-2. The key dimensions for the module increment were derived from the following criteria: the amount of circuitry required to perform a specific electrical/ electronic function, the maximum number of interface connections required, the size of the keying and retention mechanism, the method of dissipating heat from the module (conduction or forced air), handling of the modules by an astronaut under variable environmental conditions, fast remove/replace for on-board maintenance, possible repair of modules in a pressure environment, and low cost of fabrication. These considerations led to the decision of establishing a basic module with the following dimensions: 5.75 inches high by 4.00 inches deep by 0.60 inch wide. Flanges 0.60 inch wide by 0.19 inch thick were added to the ends of the module for mounting and for conducting the heat to the cold rails. The basic module also can be adaptable to forced-air cooling by enlarging the extracting fins to increase surface area.

The basic module illustrated in Figure 6-2 is comprised of the following components:

- Module Frame - made from magnesium
- Circuit Board - printed circuit or multilayer boards
- Connector Header - blade and tuning fork connecting pins (NAFI type)
- Module Keying Pins - radially oriented to accomplish the following:
  - (a) Minimize the possibility of a module being inserted into a system in the wrong location
  - (b) Prevent a module from being plugged into a system reversed

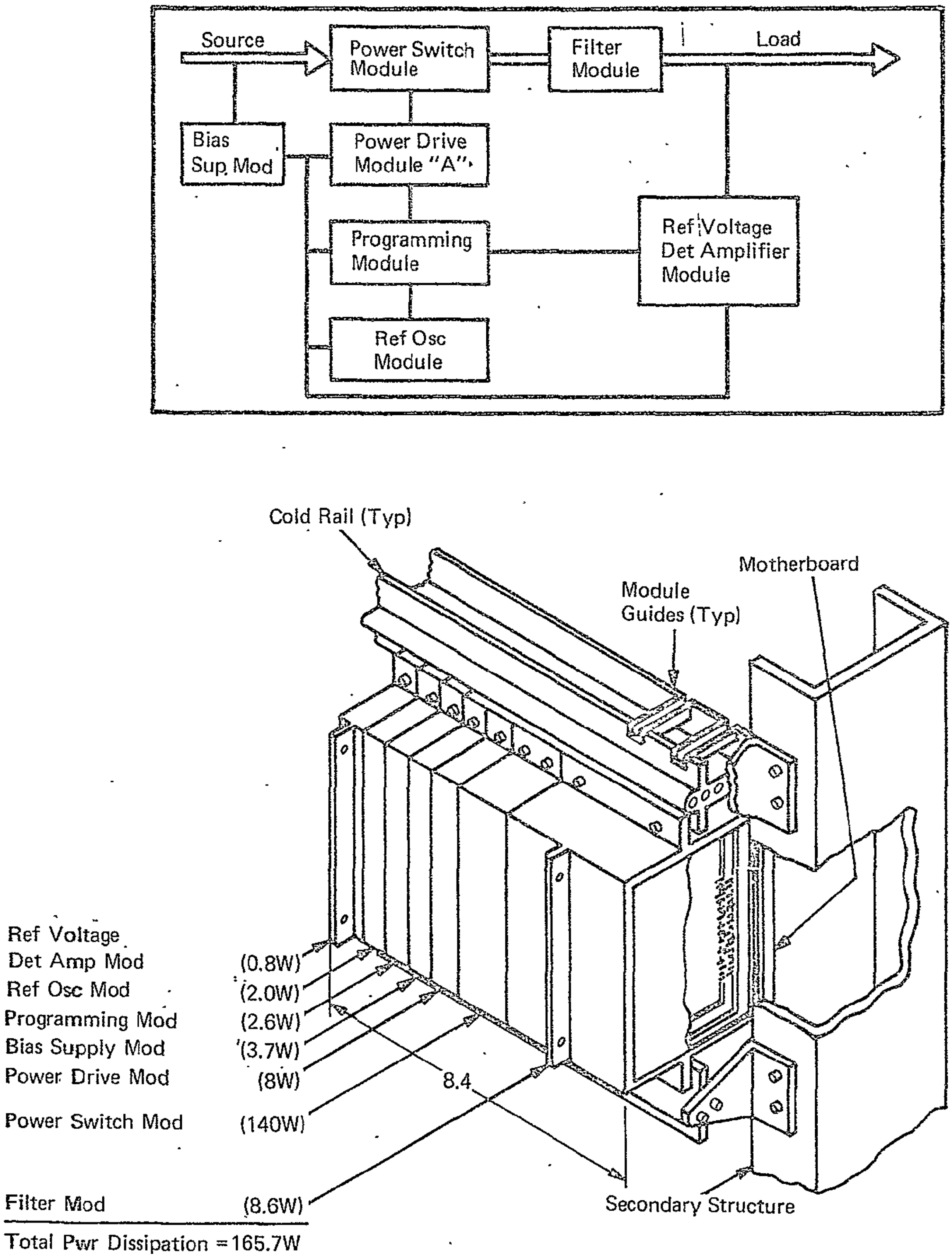


Figure 6-1. 1 KW-1ϕ INVERTER ARRANGEMENT

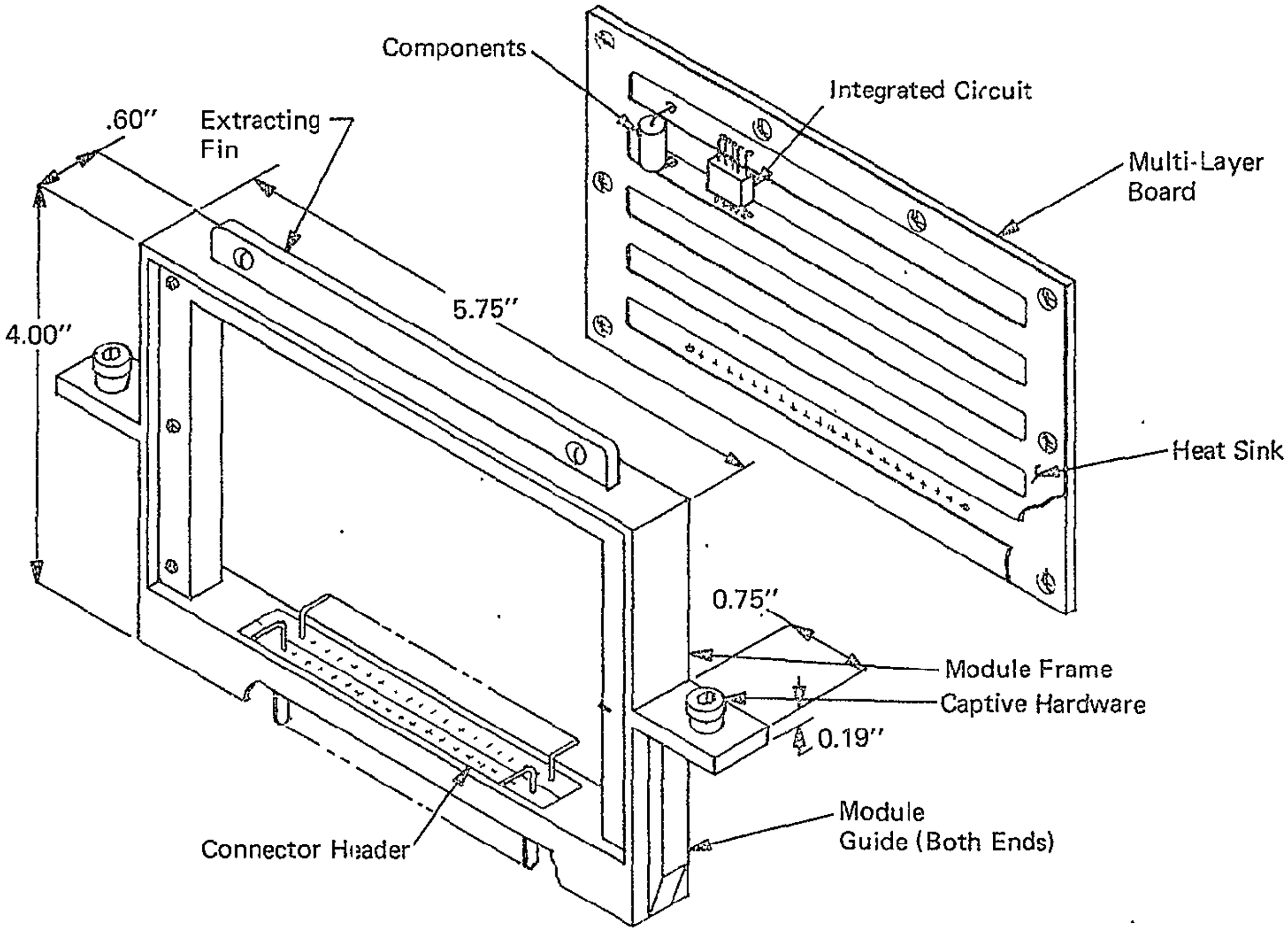


Figure 6-2. BASIC SINGLE-THICKNESS MODULE WITH DOUBLE MULTI-LAYER BOARD

(c) Assure that the module male connector contacts do not mate with the female connector contacts in the event of (a) and (b) above

(d) Assure physical protection for the connector contacts of the module

Each module increment has guide structures at each end. These guides are required to assist the proper mating and insertion of the module connector into its interfacing connector and mounting structure. Flanges at each end of the module are provided for securing to the structure.

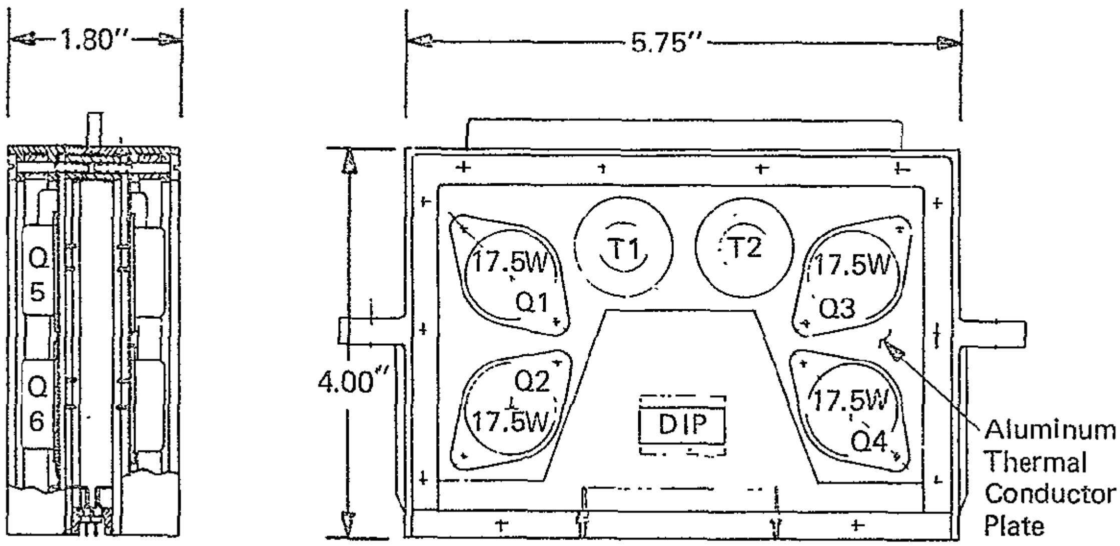
Figure 6-3 illustrates a Power Switch Module comprised of three single-thickness module frames fastened together to form one completely functional unit. Internally, the unit consists of two identical component assemblies and a common connector. This multiple-thickness module can be reduced to two single-thickness modules if the interconnections between the two modules are made through the mother board. The component boards are made of glass epoxy with a printed circuit on one side and a thermal conductor on the component side for carrying the heat to the outer frame.

The Filter Module of the 1 Kw Single Phase Inverter, illustrated in Figure 6-4, is basically similar to the Power Switch Module. This also can be broken down to two identical modules and interconnected through the mother board. Figure 6-4 also shows a typical interface between module, mother board, and cold rails.

During the design study of the 1 Kw Single Phase Inverter, a thermal design review indicated that high-power dissipation units such as the Power Switch Module (140 watts) could not be safely maintained below the recommended transistor junction temperature of $100^{\circ}C$ without altering the basic module design. In order to maintain the form factor of the basic module design and still be capable of meeting the thermal requirements, the use of heat pipes to provide a thermal shunt was investigated (see Section 6.3.3).

The second packaging study was of a 1 Kw DC-DC Converter, Figure 6-5. This unit consists of five plug-in modules. The Reference Voltage Detector Amplifier Module, Bias Supply Module, Power Drive Amplifier Module, and Programming Module are identical and interchangeable with those of the Single Phase Inverter. The Power Transfer Module is the fifth unit.

Thermal Parameters		
Item	Diss (Watts)	θ_{jc}
Power Xstr (QN)	17.5	0.9 °C/Watt
Int Circuit (DIP)	15×10^{-3}	—
Xfmr (TN)	0.5	—



Note: Thermal interface material to be used between transistor base and plate and between plate and module frame at all locations.

Figure 6-3. 1 KW SINGLE PHASE INVERTER POWER SWITCH MODULE (TYPICAL TRIPLE-THICKNESS MODULE)

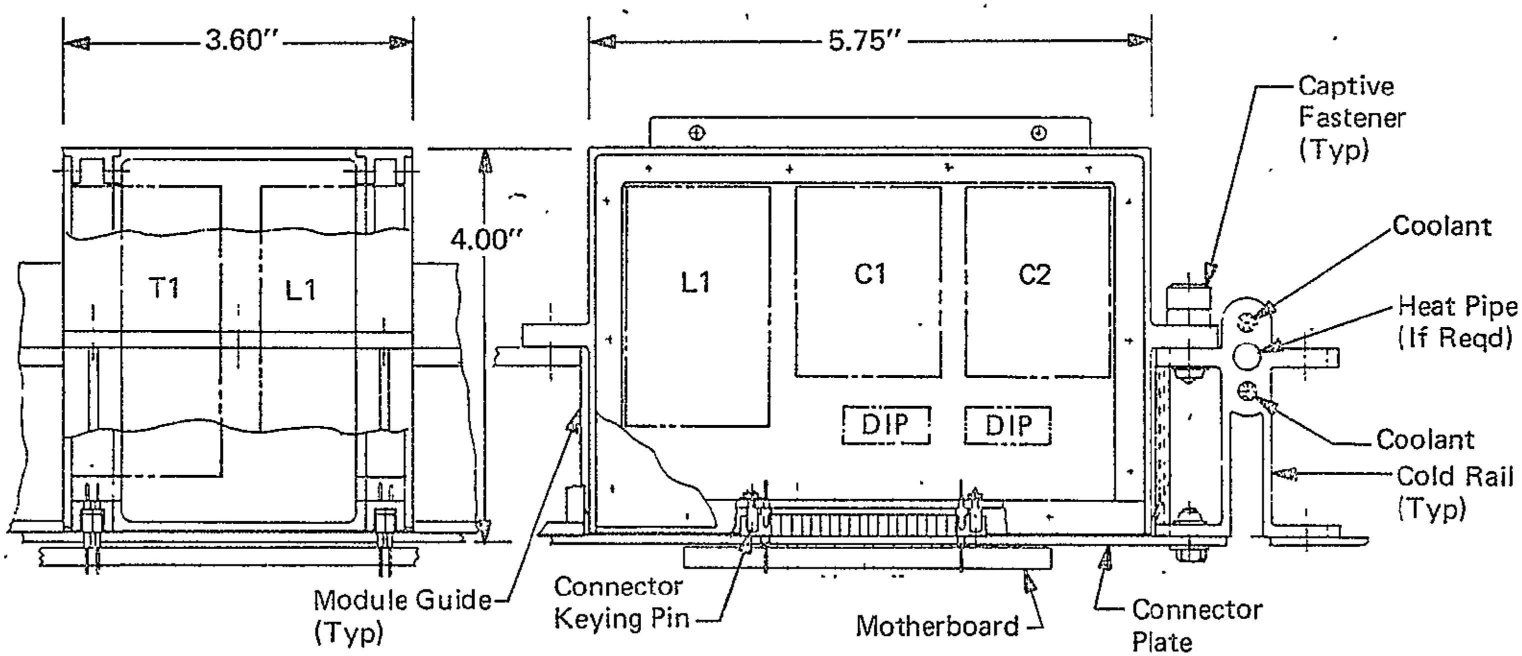
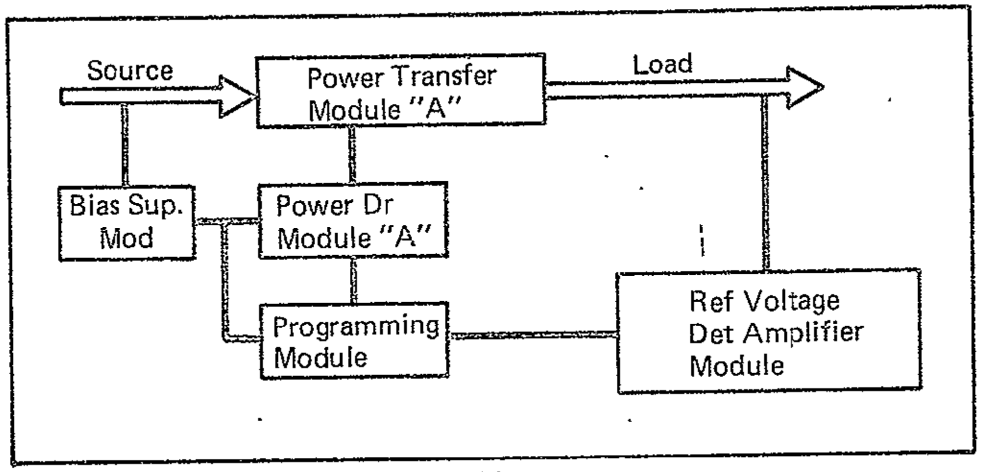


Figure 6-4. 1 KW SINGLE PHASE INVERTER FILTER MODULE
(TYPICAL MULTIPLE-THICKNESS MODULE)



Block Diagram

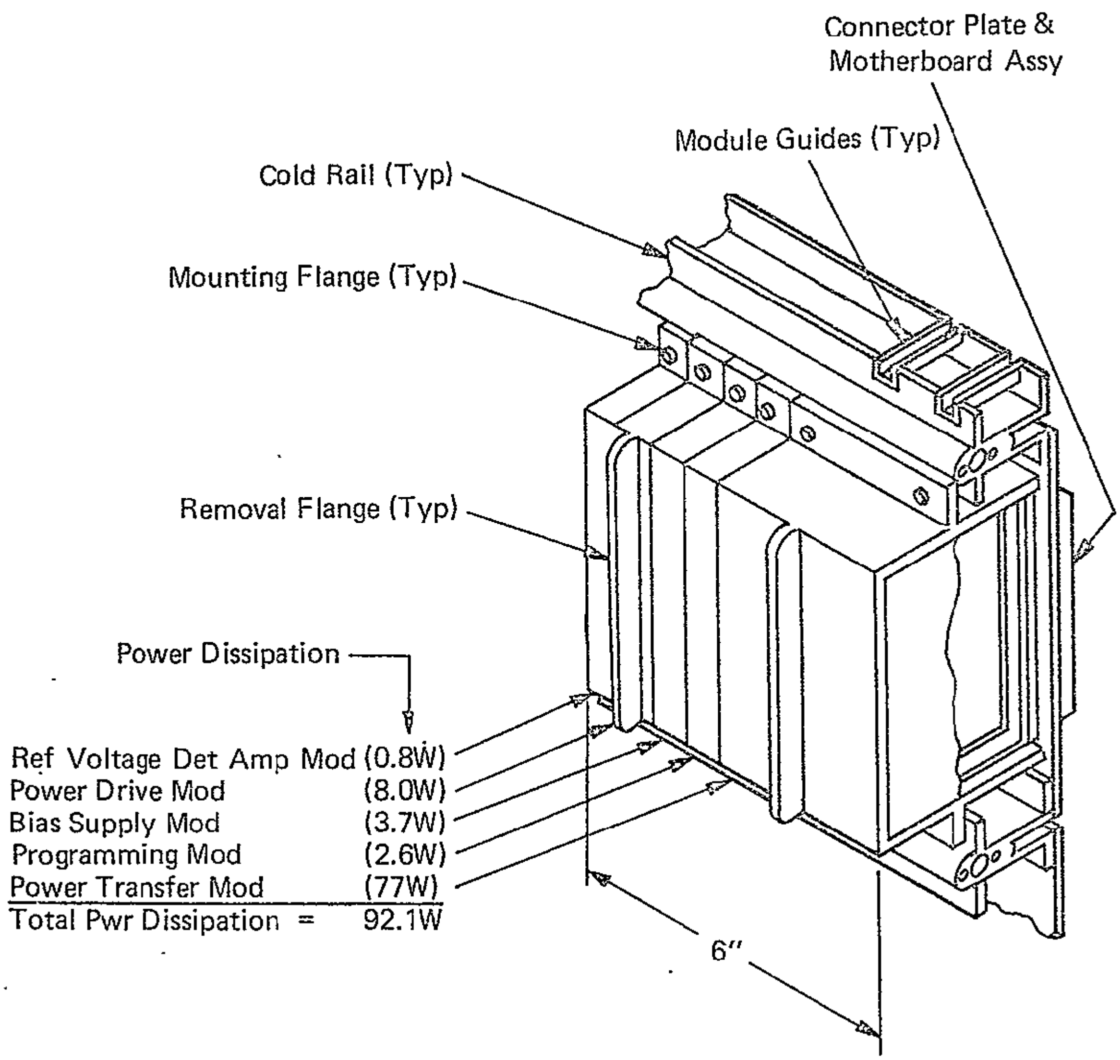


Figure 6-5. 1 KW DC-DC CONVERTER

Figures 6-6 and 6-7 illustrate two typical packaging schemes of a 1 Kw Power Transfer Module for a DC-DC Converter. The external configuration of the module conforms to the dimensions set for the basic module, 5.75 inches high by 4.00 inches deep. Because of the size of the components, the thickness of the modules is 3.60 inches, which is equivalent to a multiple of six single-thickness (0.60 inch wide) modules.

The first packaging attempt, illustrated in Figure 6-6, involved the use of rectangular heat pipes. This module uses three heat pipes, one on the component mounting plate and two inside the module structure (see Section Y-Y). Because the contact surface area between the component plate and the structure heat pipe was considered insufficient to quickly transfer the heat to the module flanges, and fabrication of the module structure appeared too costly, this concept was discarded.

The second packaging concept, which was subsequently adopted, is shown in Figure 6-7. This module also utilizes the heat pipe principle for transferring heat from one point to another. In this case, however, only two rectangular heat pipes are used, both of which are brazed to the bottom of the component plate. The close proximity between the heat pipes and mounting flanges greatly enhances the heat transfer from the components to the cold rails. Elimination of the heat pipes from the module structure also simplifies fabrication. Internally, the module is an assembly consisting of a component plate with integral heat pipes for mounting the high-power components, two component boards for low-power components, and a flexible printed circuit board interconnector. All components except the Dual In-line Packs (DIP) are point-to-point wired. This arrangement simplifies the internal assembly of the module and provides easy access for repair. Figure 5-1 shows an exploded view of the module with its three main components: housing, component assembly, and cover. A mechanical model of this module was constructed to illustrate these concepts.

A typical arrangement of a group of modules showing possible standardization of an equipment rack is illustrated in Figures 6-8 and 6-9. The standard rack can be a simple structure with cold rails and cooling lines mounted on one side (Figure 6-8) and the mother boards for module interconnection on the back side (Figure 6-9). Flat cables for interconnecting racks can be utilized to great advantage to save space and weight.

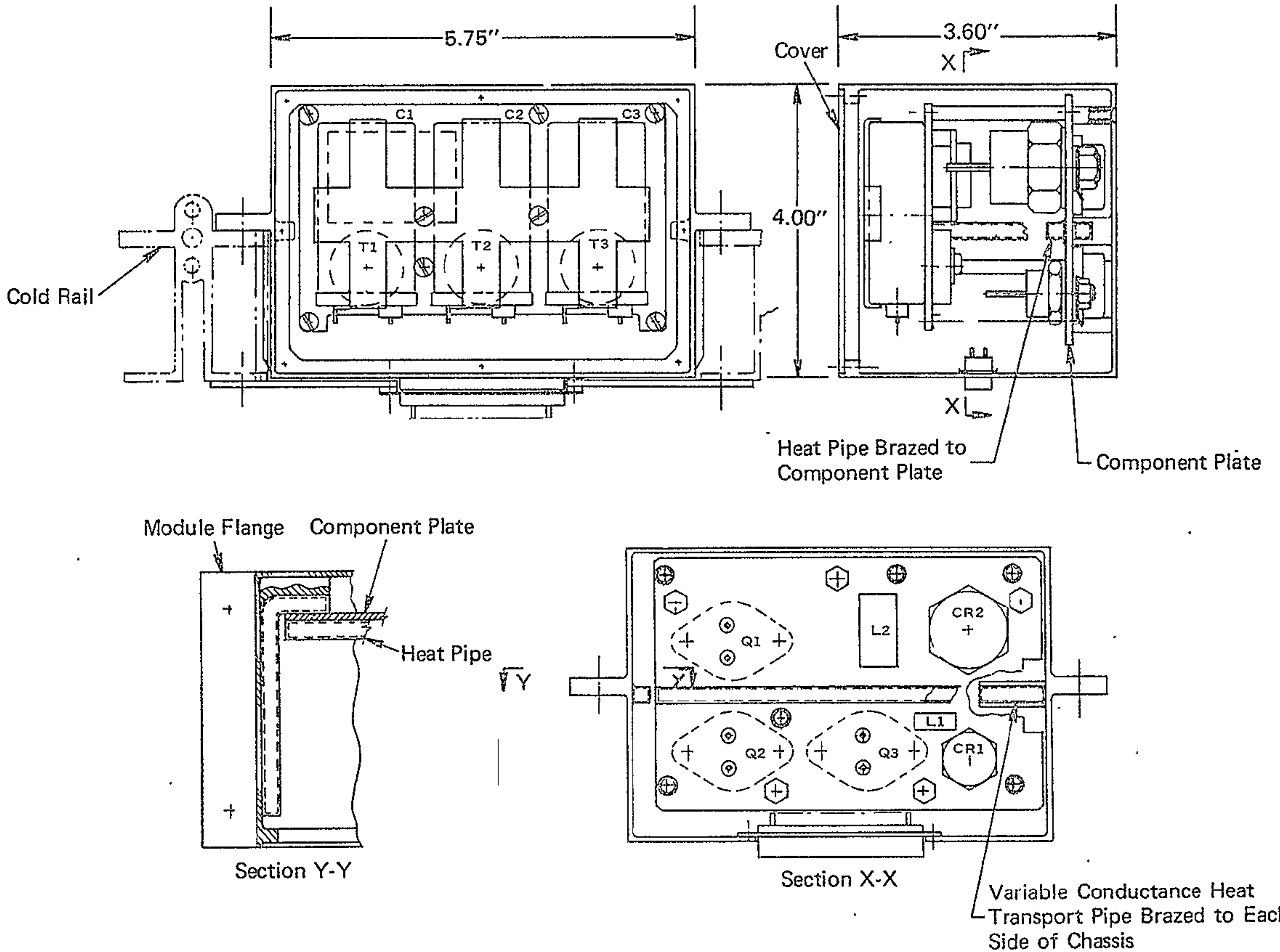
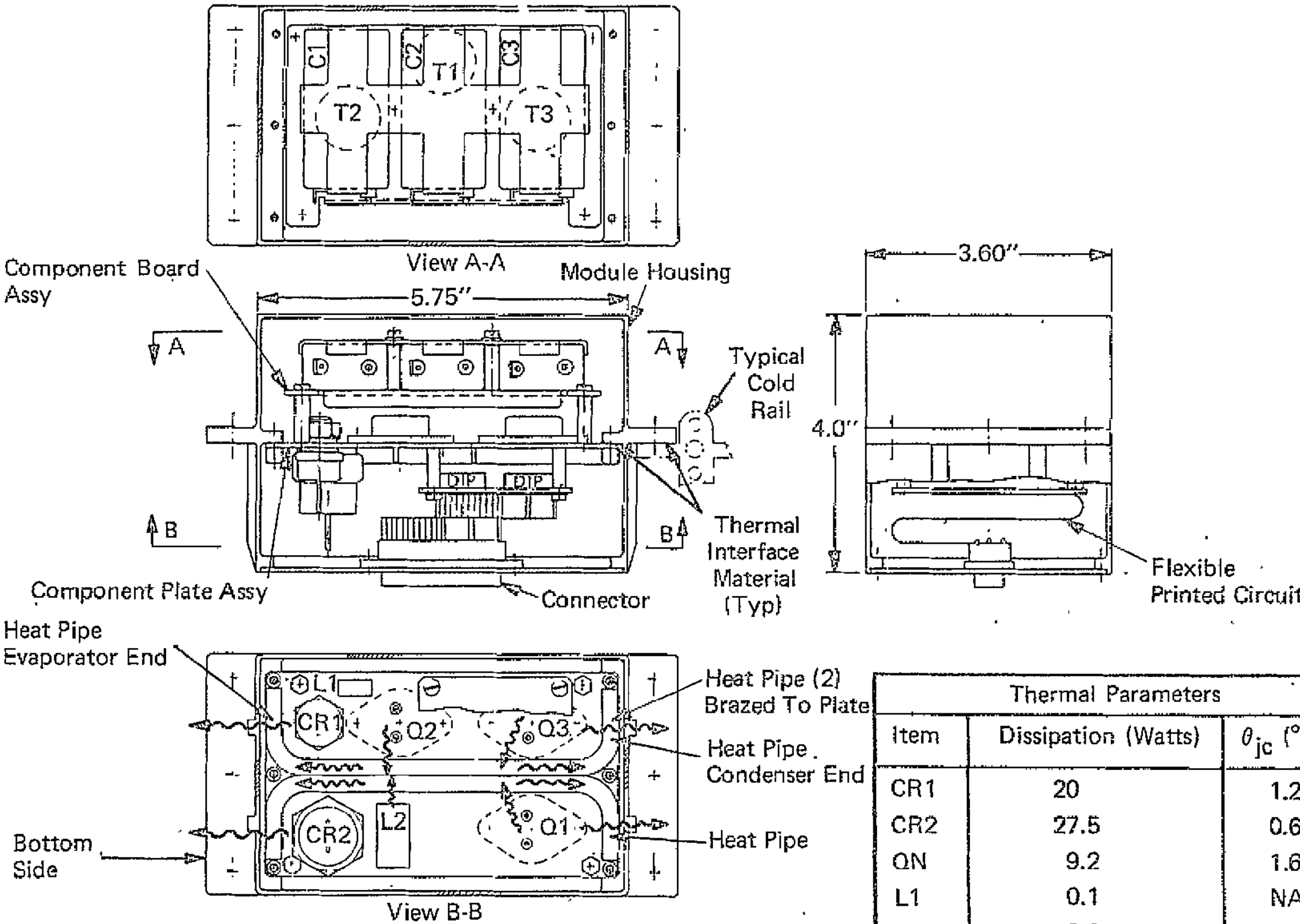


Figure 6-6. I KW POWER TRANSFER MODULE (TYPICAL), DC-DC CONVERTER/REGULATOR



Thermal Parameters		
Item	Dissipation (Watts)	θ_{jc} (°F/W)
CR1	20	1.26
CR2	27.5	0.63
QN	9.2	1.62
L1	0.1	NA
L2	2.0	NA
DIP	50(MW)	—
∿∿ Indicate Heat Flows		

Figure 6-7. 1 KW POWER TRANSFER MODULE (DC-DC CONVERTER)

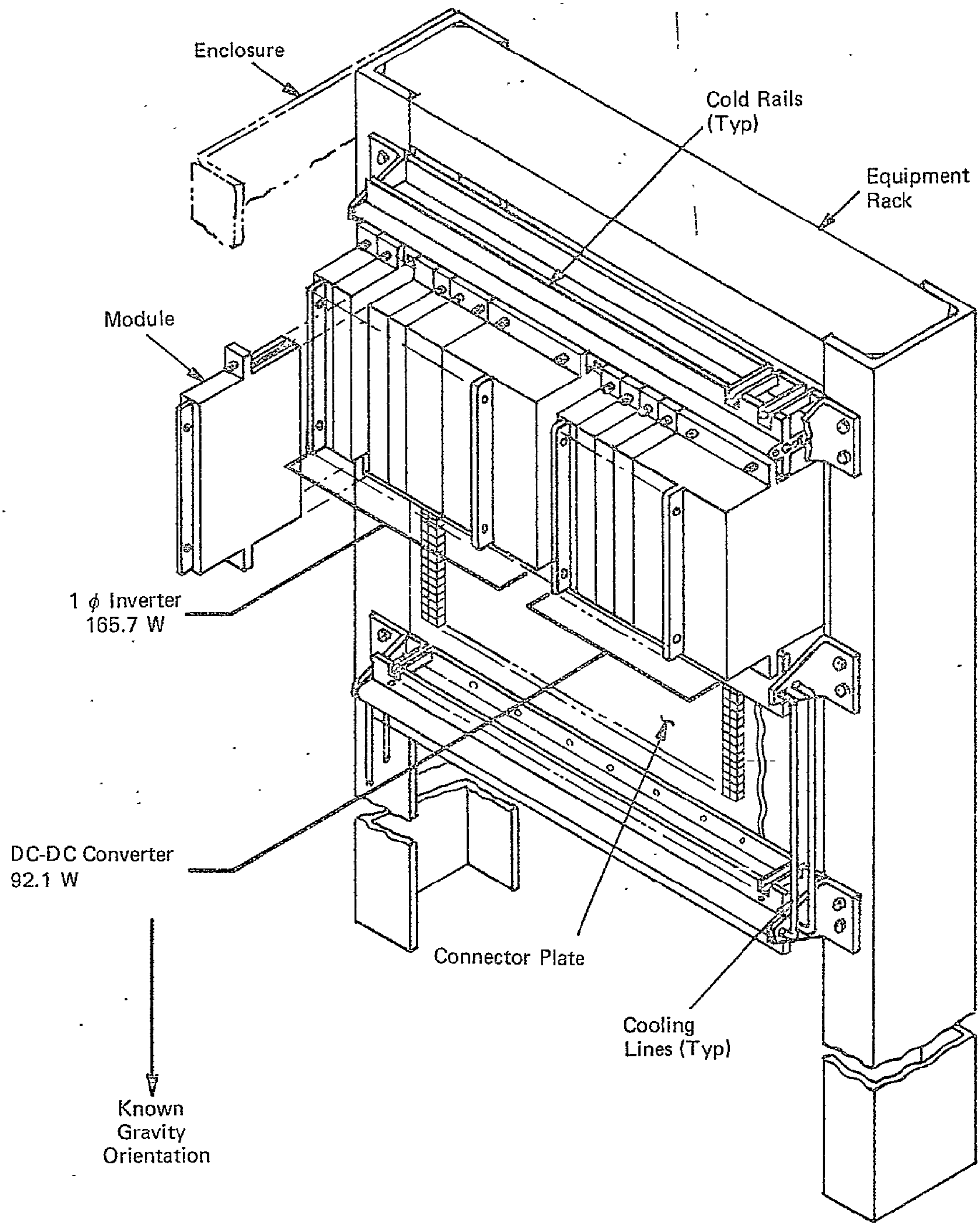


Figure 6-8. MODULE EQUIPMENT RACK (FRONT)

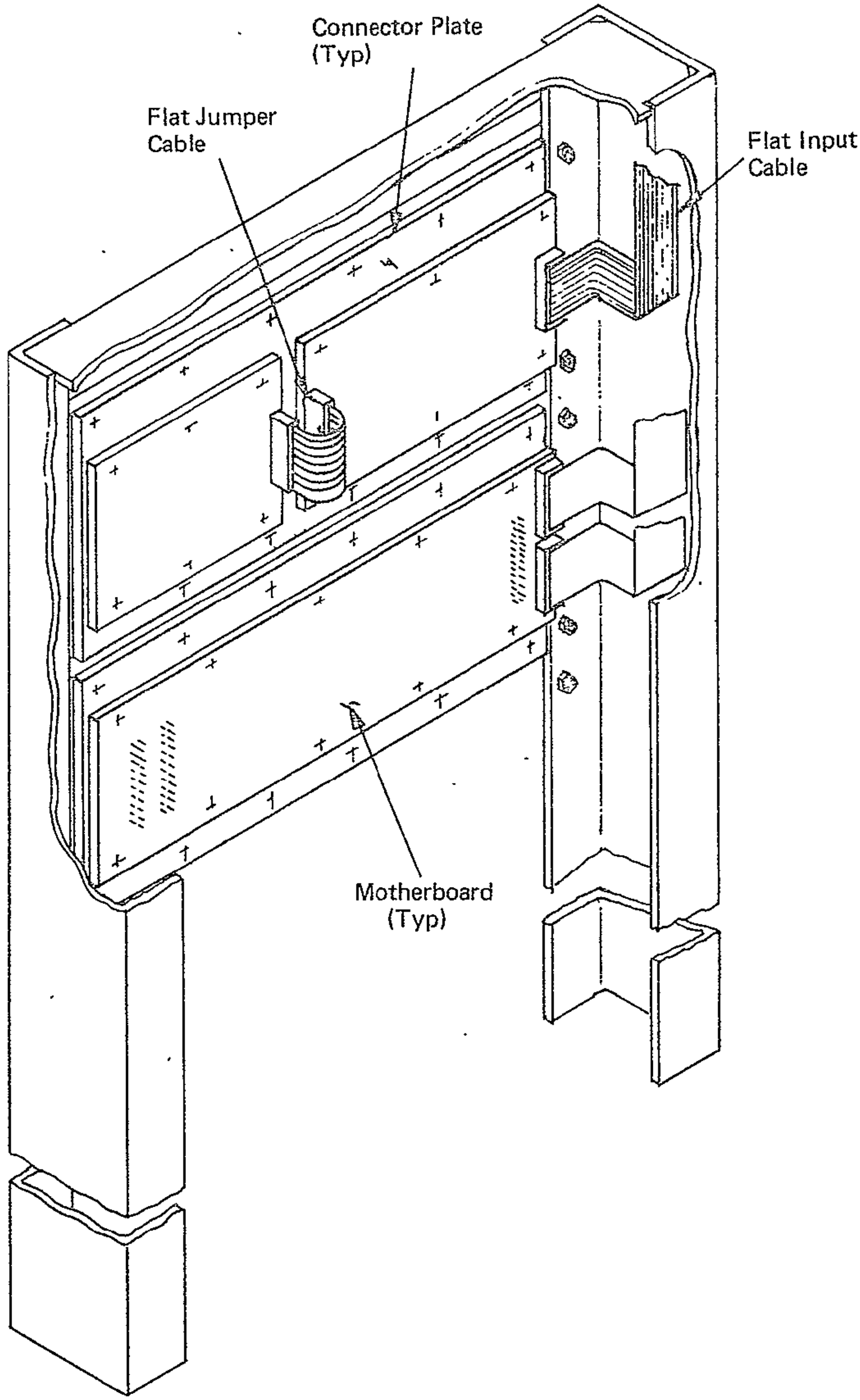


Figure 6-9. MODULE EQUIPMENT RACK (REAR)

The primary emphasis of the electrical power assembly packaging concept for space applications has been the packaging of electrical functions in a modular form. Other features of the packaging concept include conductive cooling, on-board maintenance, module standardization, advanced connectors, interconnection techniques, and EMI shielding.

Figures 5-2 and 6-10 illustrate a typical Single Phase Channel of a 25 kilowatt Cycloconverter. The Cycloconverter Power Switch Module contains 12 silicon-controlled rectifiers (Q1-Q12) dissipating approximately 55 watts each, 2 inductors (L1-L2) dissipating approximately 3.5 watts each, and 6 fuses dissipating approximately 1/4 watt each, for a total of approximately 670 watts. An attempt was made to provide a cold rail mounting arrangement similar to the Single Phase Inverter or the DC-DC Converter. The heat to be dissipated averages out to about 24 watts per linear inch of cold rail. This was considered too excessive for this type of cooling. It was decided, therefore, to package the module for cold-plate cooling. The module, 7.19 inches high by 3.38 inches deep by 16.80 inches wide, consists of a chassis with two ribs running lengthwise, a cover, and a latching mechanism. The 12 silicon-controlled rectifiers are mounted directly to two ribs. This forms a short thermal path to the mounting base of the module. The module is equipped with RFI gasketing and a quick-release latching mechanism to facilitate removal and replacement in a space environment.

The liquid-cooled mounting plate, which provides about 100 square inches of wetted area, can be mounted in the standard equipment rack shown in Figure 6-8 in place of the connector plate. Removing one flange from the existing cold rails will permit insertion of this Cycloconverter Power Switch Module within the rail spacing, thereby maintaining rack standardization. Using this approach, a mix of modules using cold rail mounting and cold plate mounting can be made within the same equipment rack. Figure 6-11 illustrates a typical arrangement of a 3-Phase 25 KVA Cycloconverter mounted in a standard rack.

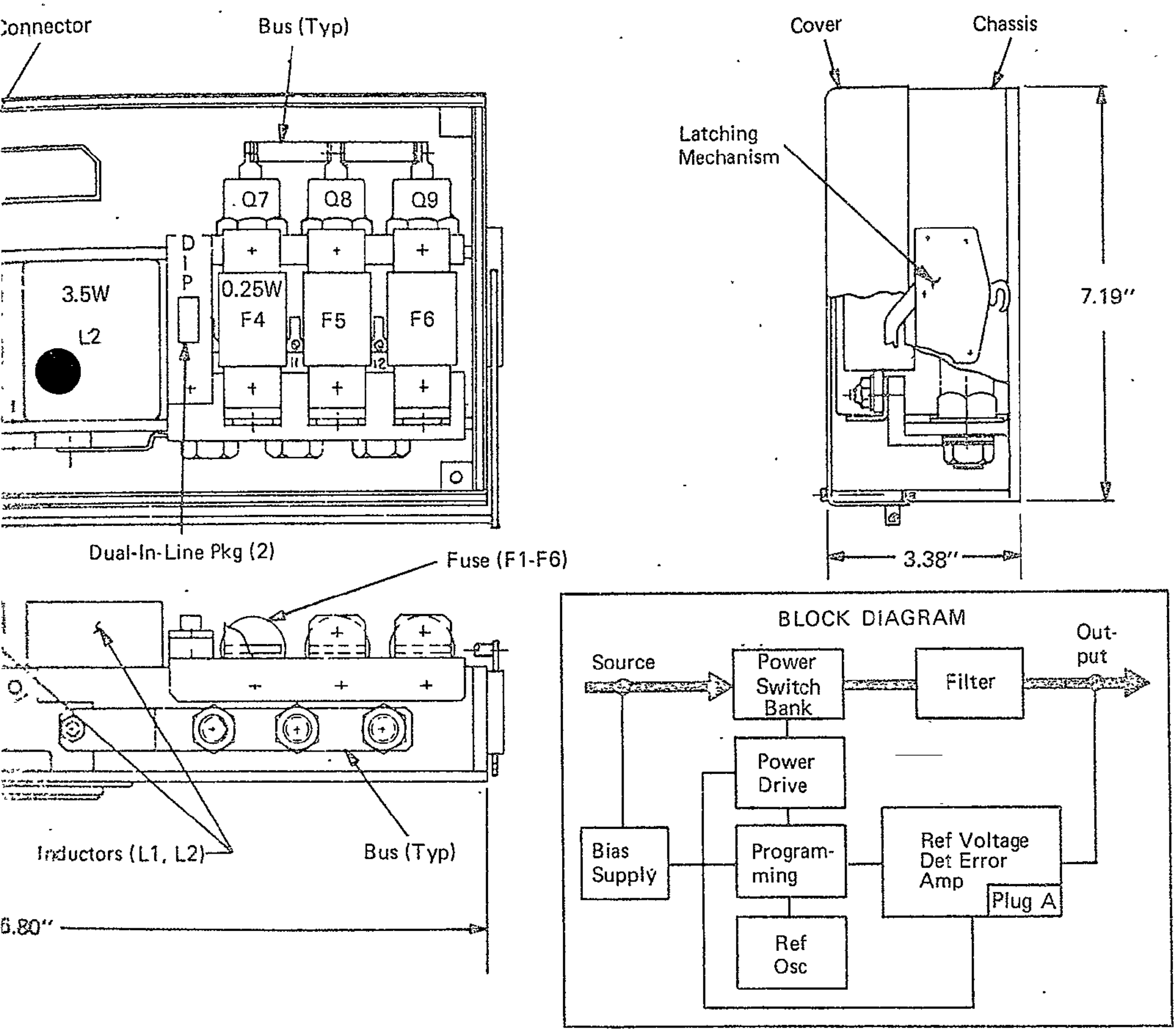
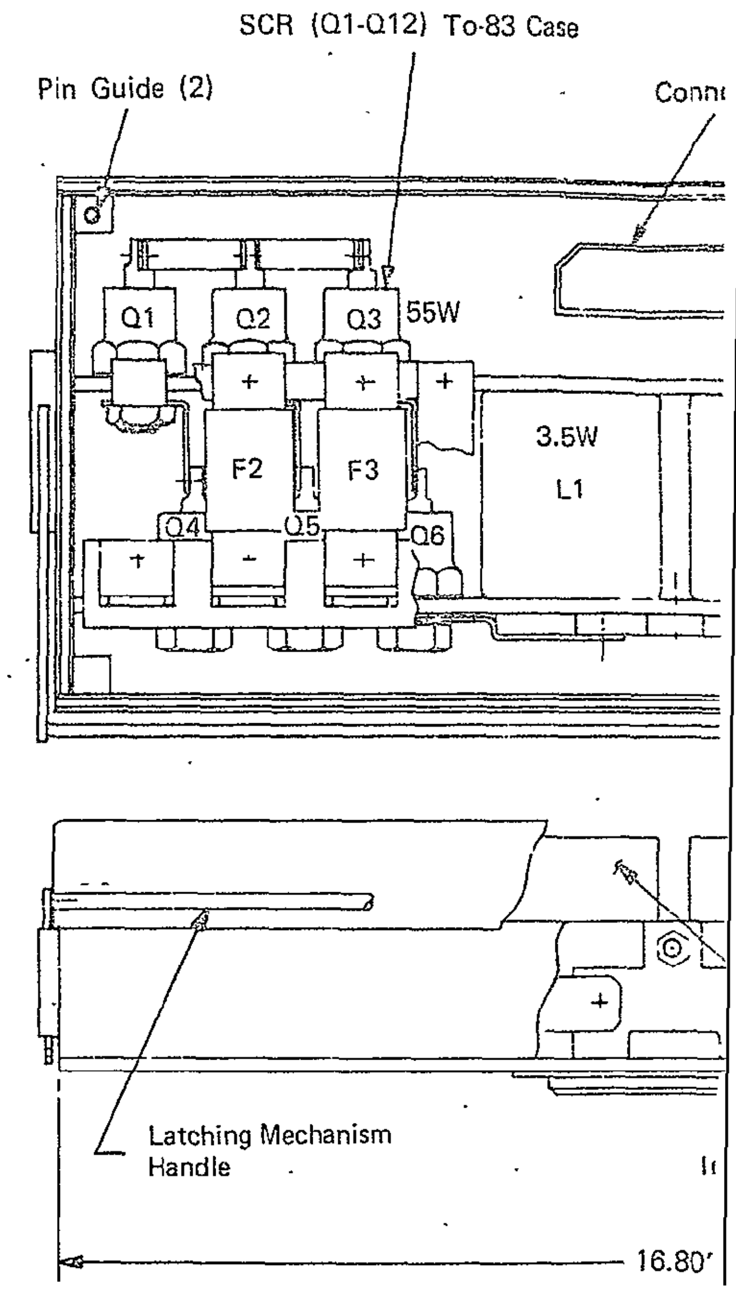
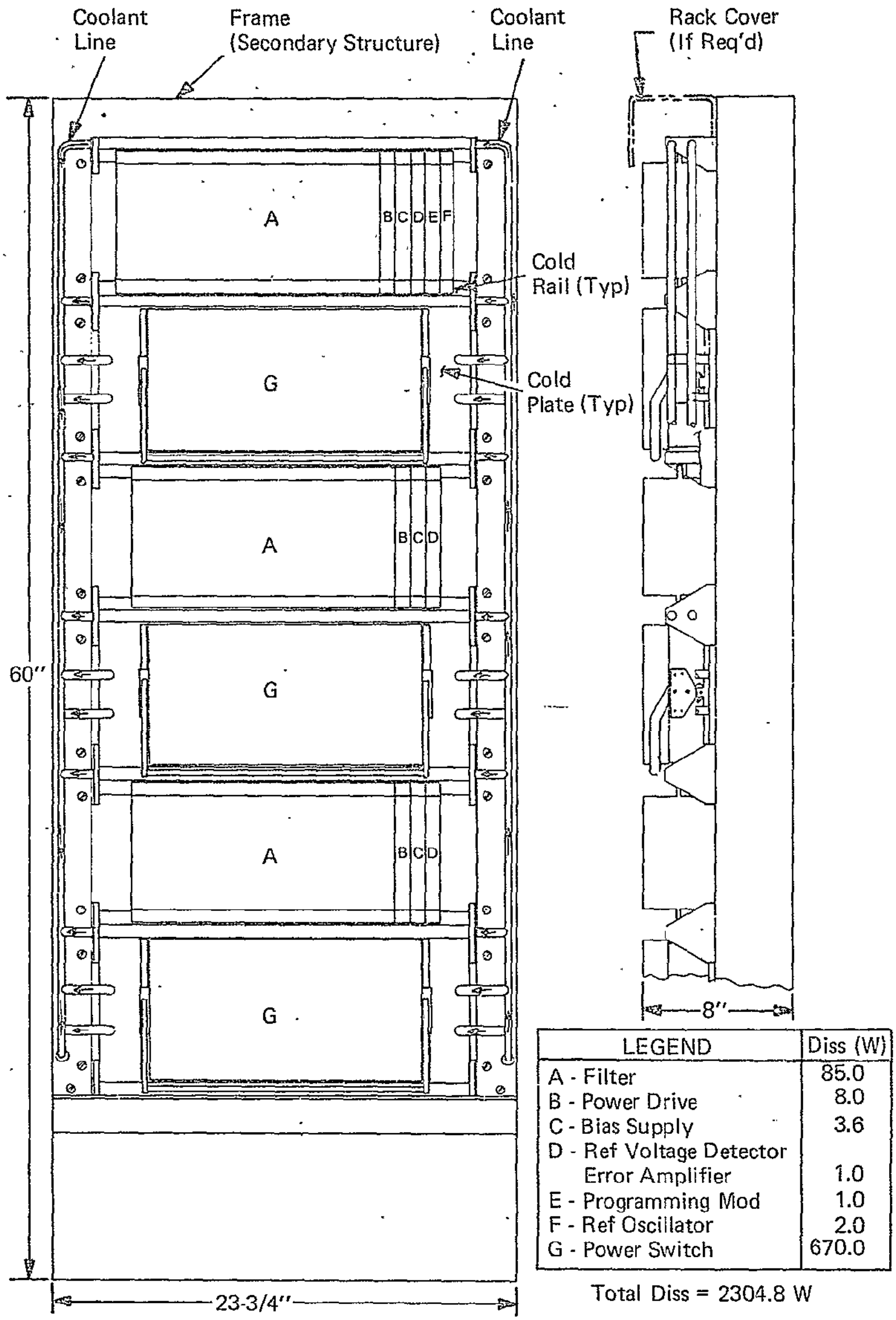


Figure 6-10. POWER SWITCH MODULE (1 PHASE) CYCLOCONVERTER



Dissipation

$Q_W = 55$ W
$L_W = 3.5$ W
$F_W = 0.25$ W



LEGEND	Diss (W)
A - Filter	85.0
B - Power Drive	8.0
C - Bias Supply	3.6
D - Ref Voltage Detector Error Amplifier	1.0
E - Programming Mod	1.0
F - Ref Oscillator	2.0
G - Power Switch	670.0

Total Diss = 2304.8 W

Figure 6-11. CYCLOCONVERTER (3 ϕ, 25 KVA), RACK ASSEMBLY

6.2 ELECTRICAL DESIGN

Three basic unit types were developed in this study.

- Inverters
- DC-DC Converter/Regulators (non-isolated)
- Cycloconverters (Frequency Converters)

Each of these devices is discussed briefly from the electrical design viewpoint.

6.2.1 Inverters

Functionally, an inverter changes DC power to AC power at a convenient utilization frequency. There are various types of power inverter designs which produce waveforms of various shapes. Since most systems require sine-wave power, the choice of inverter type depends to a large extent on the amount of filtering required to produce given distortion results. A secondary factor in the choice of circuit type is the ease with which voltage and frequency regulation can be obtained. Both factors affect volume and weight in a first order fashion. In addition, the actual operating frequency (which may be a harmonic of the desired output) affects weight and volume.

The most common types of inverter circuits are discussed in the Appendix.

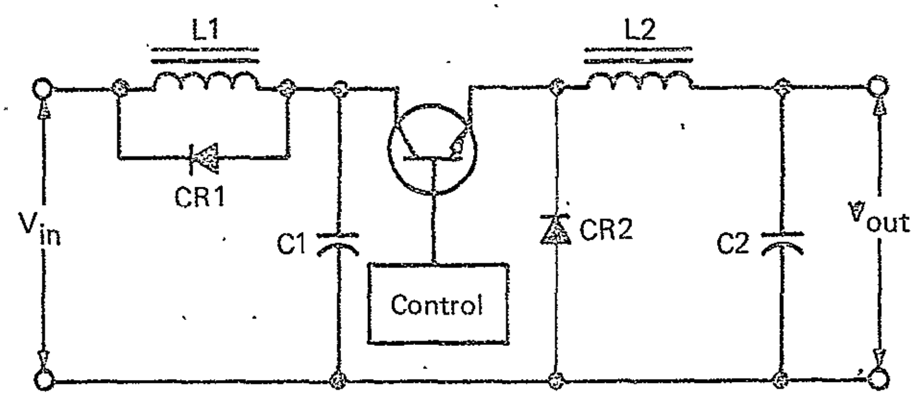
6.2.2 DC-DC Converter/Regulators

Functionally, a converter/regulator changes DC voltage levels and/or regulates DC power to closer tolerances. There are two major types of such devices:

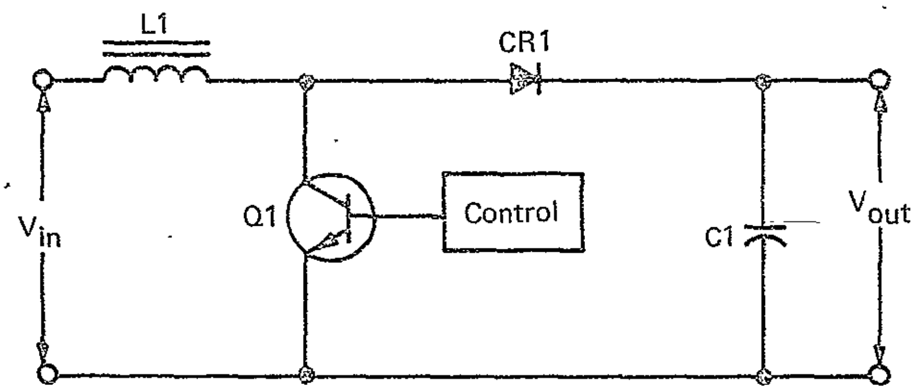
- Switching
- Proportional

The latter was not considered in this study as it is so inefficient that it is useful only where output power is extremely small or where regulation characteristics are extremely tight (approximately 0.1% or less).

Of the switching type, only the non-ohmic-isolated kind was considered, as its efficiency is approximately 10 percentage points higher than the isolated type. Two non-ohmic-isolated switching converter/regulators are shown in Figure 6-12.



a) Bucking Regulator



b) Boost Regulator

Figure 6-12. DC-DC CONVERTER/REGULATORS

6.2.3 Cycloconverters

A Cycloconverter is a device for changing one frequency, usually unregulated AC, to a lower fixed frequency. The various characteristics, performance parameters, and design criteria of these devices are relatively well-covered in the report to NASA/MSC "High Power Frequency Conversion Equipment" (Reference 23). Accordingly, these descriptions will not be covered herein. This study was based on a Naturally Commutated Cycloconverter (NCC) for the following reasons:

- Thyristors are existing state-of-the-art devices.
- Gate-Controlled Switches (GCS) required for the Force-Commutated Cycloconverter (FCC) have not been developed to the point where their use would be practical. It is doubtful that these devices will become available in time to design an FCC for the early space station.

There are, however, some differences between the electrical design assumed for this study and that derived in the above-noted contract. These differences, although of a relatively minor nature, are worth noting:

- The present study utilizes current-limiting fuses to protect the thyristors in each power switching bank. Thus, should a thyristor fail for any reason, the fuse associated with the failed device will clear sufficiently quickly to avoid chain reaction failure of the other semiconductors. Fuses are, after all, much less expensive to replace than thyristors. The associated penalties, i. e., negligible additional losses and slightly increased weight and volume, are considered acceptable. The Power Switch Module is then repairable at much less cost at a second level maintenance facility if required. Available repair facilities will determine if this is a requirement or not.
- In the design assumed for this study, projected figures based on real hardware developed for Navy programs (VSCF) showed a full load efficiency of 92.7% at 1.0 power factor, Figure 6-13. The above noted report indicates 94.4%. This is considered optimistic. At the same time, the distribution of losses among components does not appear to be consistent with information derived from real hardware.

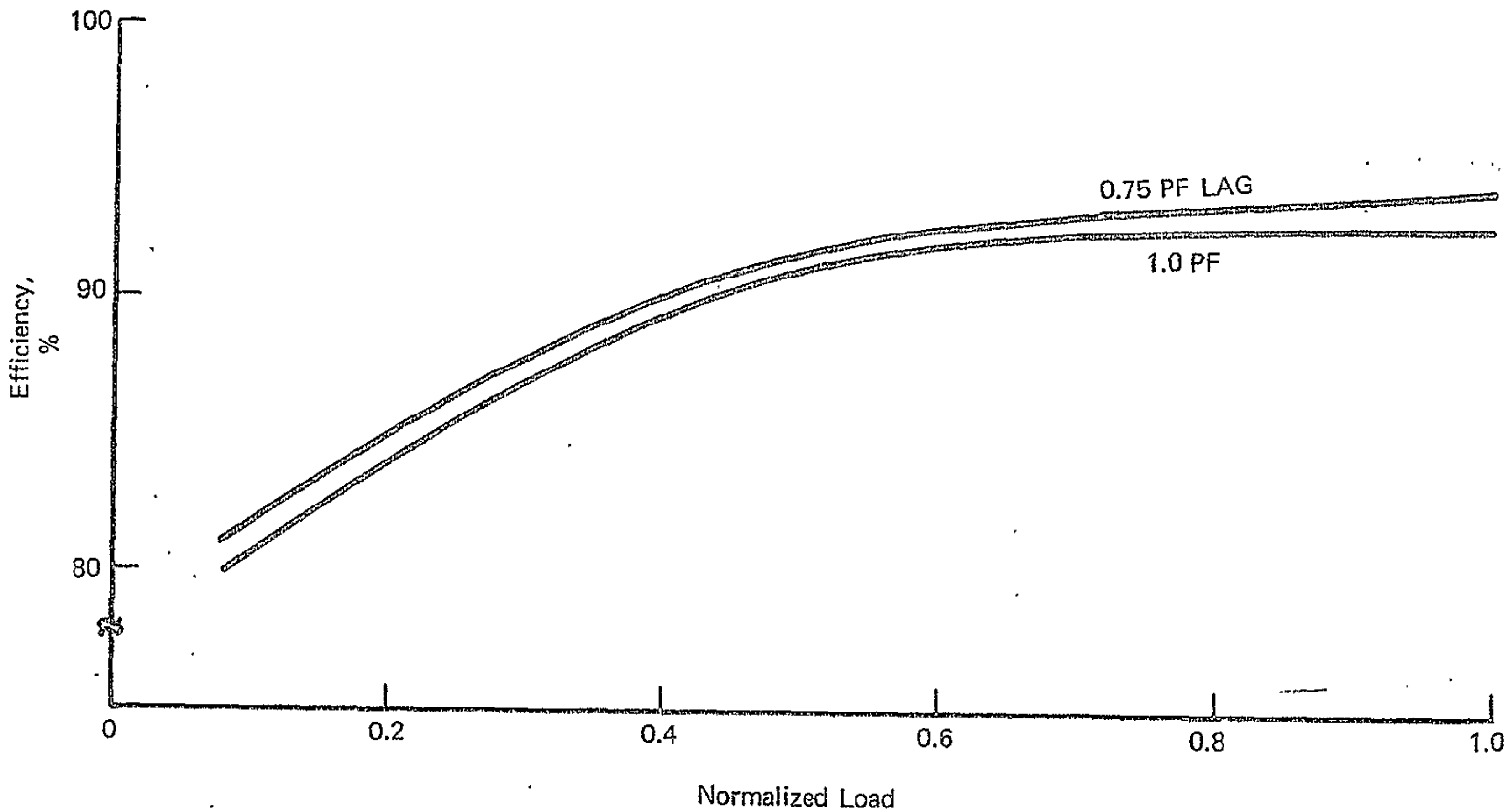


Figure 6-13. 25 KVA CYCLOCONVERTER, PREDICTED EFFICIENCY VS LOAD

6.3 THERMAL DESIGN

The thermal design study was centered on establishing approaches to provide low temperature levels for the very high thermal dissipating modules and components, insuring their desired performance and reliability goals.

Specifically, this required that the thermal designs achieve the following objectives:

- Piece part surface temperature levels shall not exceed 82°C (180°F) with solid-state junctions maintained below 100°C (212°F) during worst load conditions.
- Thermal interface dissipation density level shall be compatible with reasonable environmental control system capabilities.
- Permit the thermal interface to provide ease of maintenance and maximum standardization of packages.
- Approach the thermal design so as to impose little or no constraints to the functional circuit and packaging design.

6.3.1 Background

The three methods by which heat may be transferred are conduction, convection, and radiation.

Conduction involves the transfer of kinetic energy from one molecule to another. Because of the temperature range and configuration inherent to electrical designs, this mode of transfer is predominant. For given temperature differences more heat usually can be transferred by conduction than by either convection or radiation.

Heat transfer by conduction is governed by Fourier's law, which may be stated as follows: The rate of heat flow (h) through a slab of material is proportional to the cross-sectional area (A) of the slab, proportional to the temperature difference (ΔT) across the slab, and inversely proportional to the thickness or distance of flow (L). The constant of proportionality is the "Thermal Conductivity" (κ) of the material, measured in cal/cm-sec-°C or, in simpler units, watts/°C. Fourier's law expressed mathematically is

$$h = \frac{dq}{dt} = \frac{\kappa A}{L} (T_2 - T_1) \tag{1}$$

where T_2 = Temperature of the hot side of the slab

T_1 = Temperature of the cold side of the slab

From this relationship it is quite apparent that, to require minimum ΔT (low temperature rise) and to limit the available materials (conductivities) and cross-sectional area (weight), the reduction of heat flow paths (L) is the prime factor in producing high heat flow capability. All the packaging designs reflect this basic thermal design consideration.

Convection involves the transfer of heat by the mixing of fluids; it is primarily a process for heat transfer from a solid to a fluid in contact with it. Analytically, heat transfer by convection cannot be expressed as neatly as transfer by conduction; however, it is common practice to mathematically express this heat flow as

$$h = \frac{dq}{dt} = h_f A (T_2 - T_1) \tag{2}$$

where the rate of heat flow (h) is a function of the surface area of the solid in contact with the fluid, the temperature difference between the fluid and the solid, and the effective film coefficient (h_f) which is a complex term derived from the velocity of the fluid at the solid's surface, the fluid temperature, and certain physical fluid properties.

The thermal design objectives include operational requirements during periods of zero g and, since natural convection must rely on fluid (air) density changes and gravity to produce fluid velocity, the h_f term in the equation (2) would go to zero as would the heat flow. A solution employing forced circulation or fans internal to equipments for the high dissipation levels of these designs would impose severe power and noise requirements and must be discarded. Convective heat transfer for these module designs was limited to the secondary heat sinks such as the equipment cold rails and cold plates.

The need for an active coolant loop was established in this design due to the magnitude of the total loads and a supplementary knowledge of overall Space Station and Space Shuttle Environmental Control Systems requirements.

Thermal radiation is the transfer of heat by electromagnetic radiation, and is the only means of heat transfer between bodies separated by a vacuum. Heat transfer by radiation is also more difficult to analyze than transfer by conduction. The rate of transfer between two bodies can be defined simply by

$$h_{2-1} = \sigma F \epsilon (T_2^4 - T_1^4) \tag{3}$$

where h_{2-1} = Net heat flow rate, watts

σ = 5.67 X 10^{-12} watts/cm^2 - $^oK^4$ (Stefan-Boltzman constant)

T_2 = Hot body temperature, ^oK

T_1 = Cold body temperature, ^oK

F = View factor, emitter to receiver

ϵ = Surface emissivity

A = Emitter area, cm^2

This equation becomes very complex as multiple surfaces with respective views, reflectances, and temperature differences are considered. Despite the fourth power in the temperature difference, the small value of σ renders this mode of heat transfer very small when considering desirable low internal black box temperature gradients. To provide thermal design conservatism and to simplify the design analysis, internal module heat transfer by radiation was neglected when evaluating the thermal design suitability. This mode of transfer, however, would govern all internal unfilled interfaces during vacuum conditions and has resulted in a special effort to reduce the number of such interfaces to a minimum. A detailed discussion of investigations in the area is provided in Section 5.2.

6.3.2 1 Kw Single Phase Inverter Assembly

Figure 6-1 shows a typical 1 Kw Single Phase Inverter made up of seven separate functional packages. The first objective of the thermal design was to establish a basic desirable configuration within which to design the mechanical package.

From the studies conducted under the Lunar Module (LM) Electronics packaging program (Reference Grumman LMO-360-98 LEM Electronic Packaging), the weight tradeoff and thermal design desirability of the center flange-mounted electronics was established.

In addition to structural and Center of Gravity (CG) type mounting advantages, the important thermal achievement was to provide the shortest equal thermal distances from the mounting flange to the box's internal extremities or components. The actively cooled structure's mechanical mounting flange provides a suitable reference heat sink.

The next step was the selection of a standard package or module form factor. The 4.0 X 5.75 inch package was settled on as a compromise between the thermally desirable shortening of the heat flow paths (LM presents a 7.0 X 6 0 inch cross-section form factor), the electrical circuit layout, and the packaging considerations typical of the various circuits under design.

The high dissipation levels typical of these circuits require very close design coordination between the circuit, packaging, and thermal disciplines to insure suitable low component temperature levels. Special attention was paid to part location heat flow paths, materials, and thermal interface control. Parts with high dissipation levels were located as close to the mounting flanges as possible to minimize any additional heat conductor requirement and subsequent weight increase.

The power dissipation levels for the Inverter assembly are depicted in Figure 6-1. Of the seven modules, the Power Switch represents the most critical dissipation problem ($3.2\ w/in.^3$), and thus was chosen for detailed thermal analysis and Environmental Control System (ECS) interface evaluation for the Inverter designs.

Figure 6-3 shows the recommended design approach and the piece part thermal parameters.

A thermal conductor plate was utilized to provide a high conductance path from the 17.5 watt transistors to the module frame. Thermal conductance was determined for a typical cross-section and material of the module frame (Figure 6-14) together with the transistor junction-to-case thermal resistance θ_{jc} and used to predict junction temperature levels. The thermal capacitance of the design was omitted as it is not required in a maximum steady-state analysis.

Figure 6-15 represents a thermal network analog for the expected temperature rises (ΔT_N) in the circuit. This analog is considered conservative since it does not include the

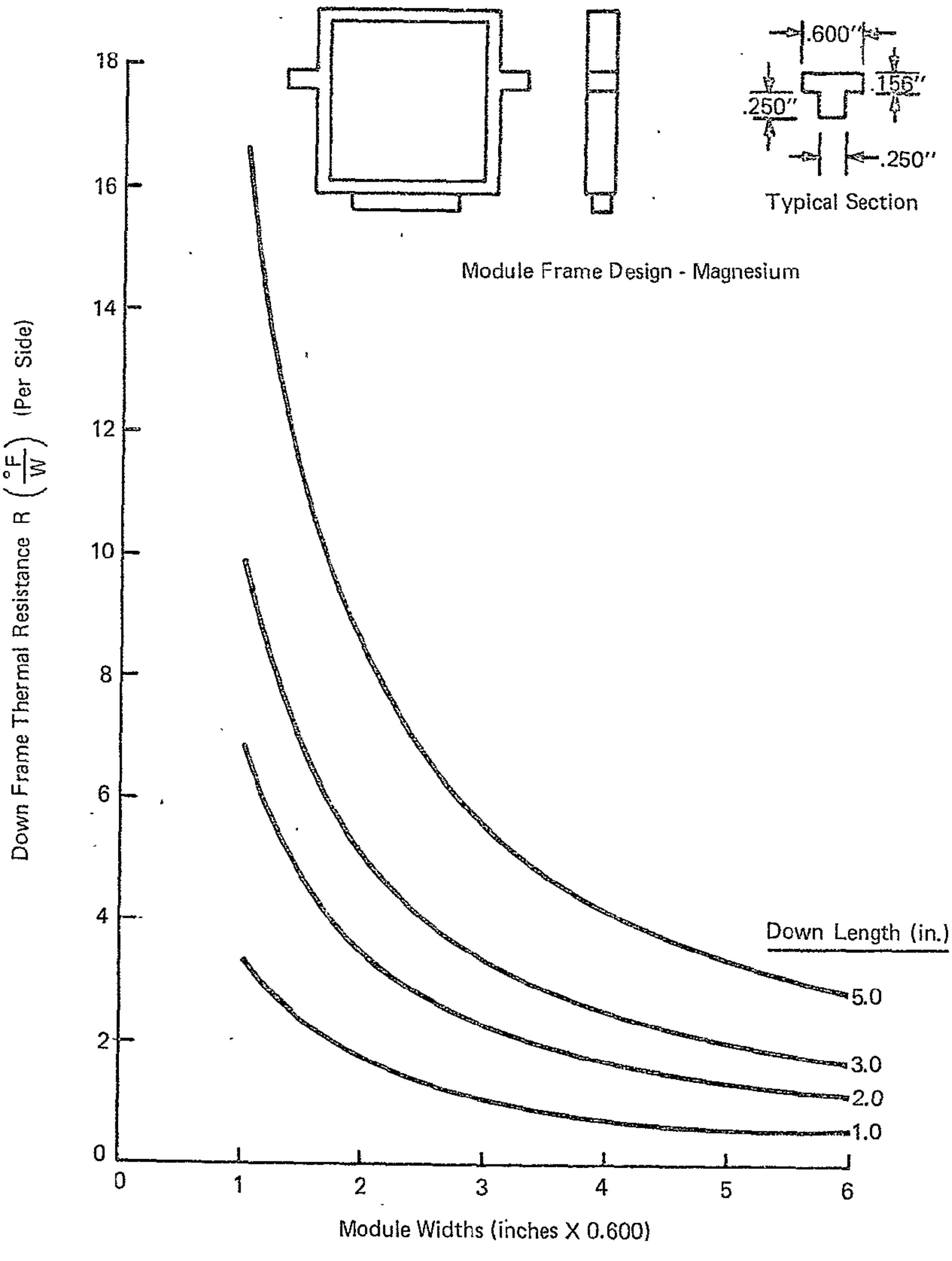
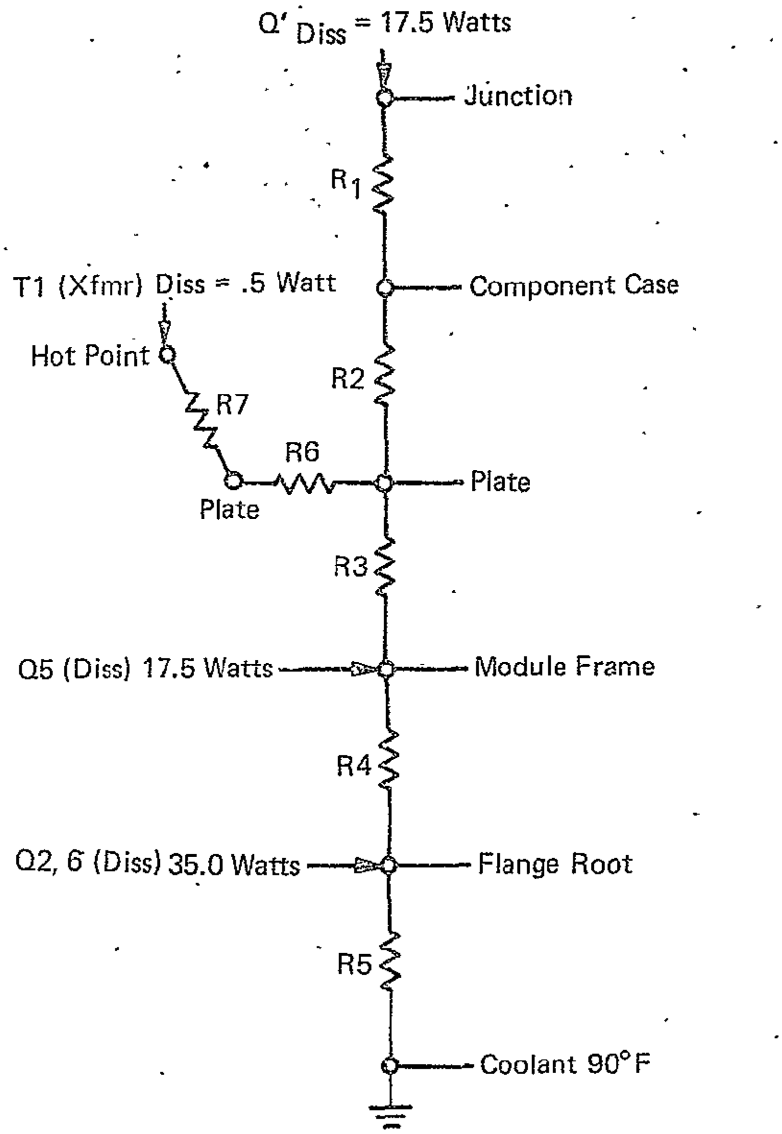


Figure 6-14. THERMAL RESISTANCE, TYPICAL MODULE FRAME



R (°F/W)	ΔT (°F)	ΣT (°F)
		205.1
(θ_{jc}) 1.6	28.0	
		177.1
.056	0.98	
		176.1
1.2	21.0	
		135.1
0.8	28.0'	
		127.1
0.56	37.1	
		90.0

Total Power Dissipation To Coolant Per Side = 4 X 17.5 = 70 Watts

Legend: Thermal Resistance

R1 = Junction to Case (θ_{jc})

R2 = Case thru Interface Material to Conductor Plate

R3 = Resistance Along Plate Thru Interface To Module Frame

R4 = Resistance Down Module Frame To Flange Root

R5 = Effective Resistance, Flange Root To Coolant Including Diffusion Effects of Center Rail Heat Pipe.

R6 = Plate Resistance Transistor to Transformer Location.

R7 = Resistance From Transformer Base Thru Interface to Hottest Point in Transformer Coils

The depicted junction temperature of 205°F (96.1 °C) is in a satisfactory range. During a design phase, optimization of design can be achieved by establishing weight penalties for each Δ T improvement increment.

Figure 6-15. SINGLE PHASE INVERTER, POWER SWITCH MODULE-THERMAL NETWORK ANALOGY radiative heat transfer as previously mentioned. An incoming coolant temperature of 90°F was assumed in keeping with expected Space Station or Shuttle ECS design parameters.

6.3.3 General Coolant Interface - Cold Rails

The internal symmetry of the Power Switch Module dissipation provides for the equal division of heat flow to each mounting flange. The environmental control system interface dissipation for this most critical rail-mounted module is 38.8 watts/linear inch. This value is approximately 13 times the 3.0 watts/linear inch maximum design value reflected in the Lunar Module cold rails and thus requires special consideration.

A preliminary evaluation of total power dissipation for the entire Inverter assembly showed a total of 166 watts. This is not far in excess of the present cold rail capability considering the distance of 9.0 inches covered by the entire assembly. A further evaluation showed the limiting thermal resistance to be between the effective short length of heat input section on the rail and the effective resistance at the wetted coolant interface. To improve this limitation, methods of spreading or diffusing the heat to increase the coolant-wetted effective area were investigated. An increase in rail material thickness was an obvious approach, but this would render undesirable weight penalties.

In light of the emerging technology in the area of thermal heat pipes, this approach was evaluated. Applying a heat pipe provides a high-capacity isothermalizer rendering excellent weight and functional advantages. Figure 6-16 depicts a developed configuration.

All dimensions for coolant passages, heat pipe diameter, and rail thickness are sized for approximate capacity. An optimization of capacity, width, and weight trade-offs are performed during a normal design phase.

The capacity of the rail design is defined by two parameters: (1) peak localized input, limited to any two-inch long section on the rail mounting flange, and (2) the total maximum average heat absorption rate applicable to the entire rail length. Both parameters must be satisfied for adequate rail performance. The overall rail capacity is also a function of the mean coolant temperature. Figure 6-17 illustrates the expected range of capacity and shows the expected design point.

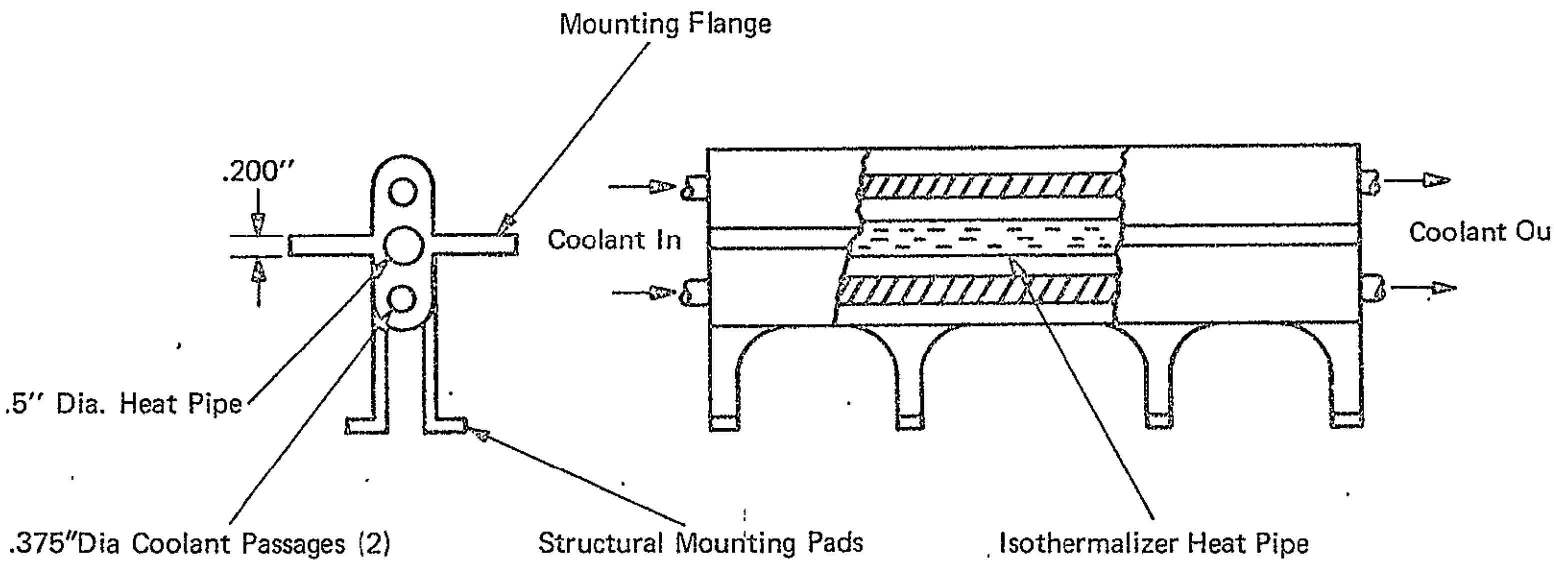


Figure 6-16. HEAT PIPE - COLD RAIL

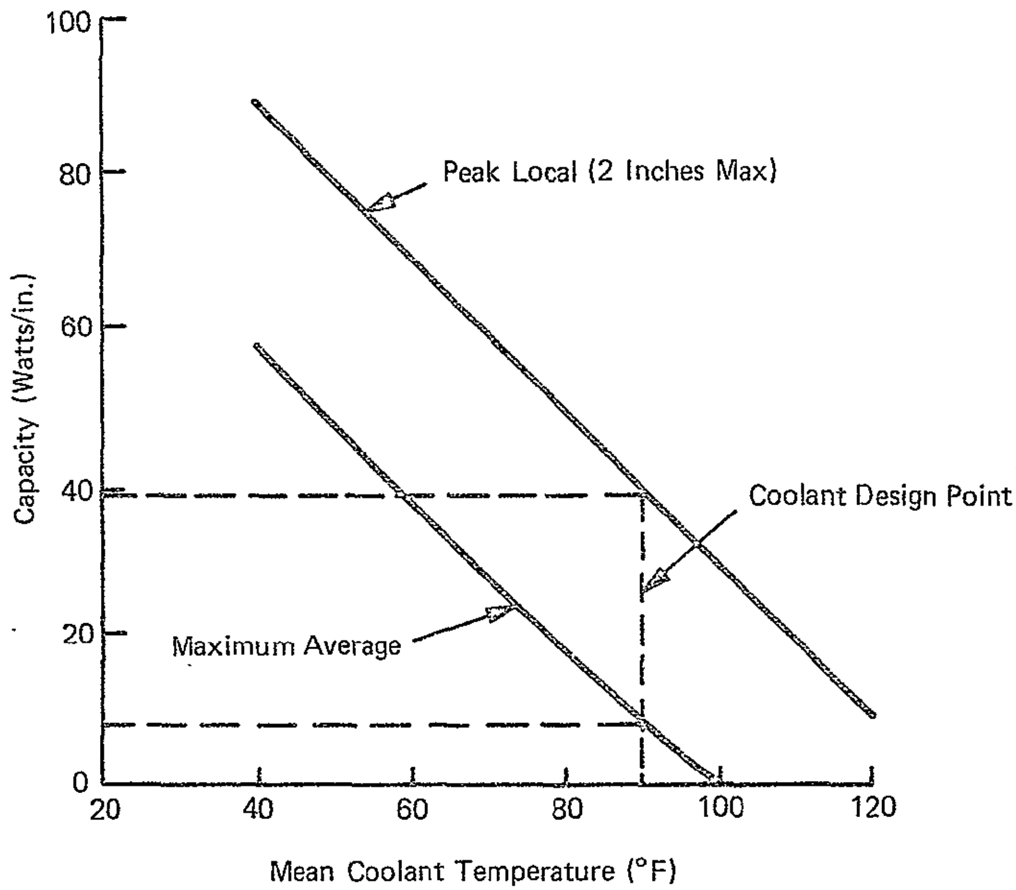


Figure 6-17. HEAT PIPE COLD RAIL CAPACITY

The overall thermal resistance coupling (module frame flange root to coolant) to a twin coolant passage cold rail, without a heat pipe, is predicted at 2.8°F/watt/linear inch. At this value of resistance, the 38.8 watts/inch interface dissipation rate of the Power Switch Module would produce a 105°F temperature rise to the flange root. Assuming the coolant at 90°F results in approximately 195°F at the module frame and would be prohibitive considering a desired 212°F at internal component junctions.

Further evaluation shows this overall resistance to be made up of the series sum of the resistances of the flange length, the module-to-rail structure, the rail structure to the fluid area, and the fluid area film coefficient to coolant. Since the pure conductive elements can be improved by thickening of material cross-sections, the limiting resistive elements are the mount interface and the fluid film terms.

Using a joint interface silicon grease (reference discussion in Section 5.2), an interface conductivity of 1000 Btu/hr/ft^2/°F can be obtained. This value, analyzed for the Power Switch flange area, results in a suitable resistance value of 0.45°F/watt.

The fluid-to-rail interface appears more difficult to improve. This resistance is derived from the expression

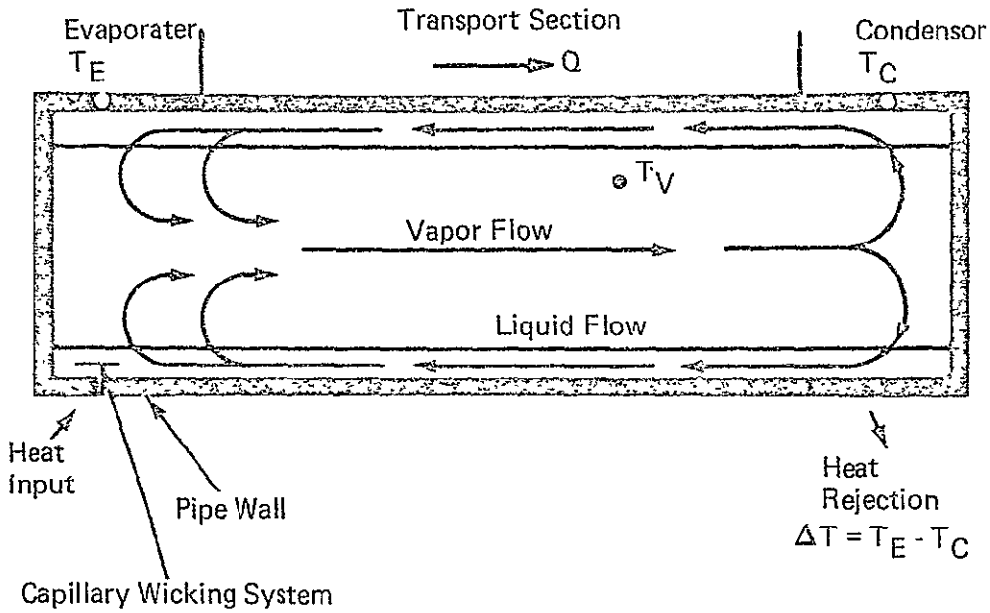
$$R = \frac{1}{hA}\left(\frac{^\circ F}{w}\right)$$

where h = fluid film conductance coefficient, w/°F-in.^{2}

A = effective pipe wetted surface area, in.^{2}

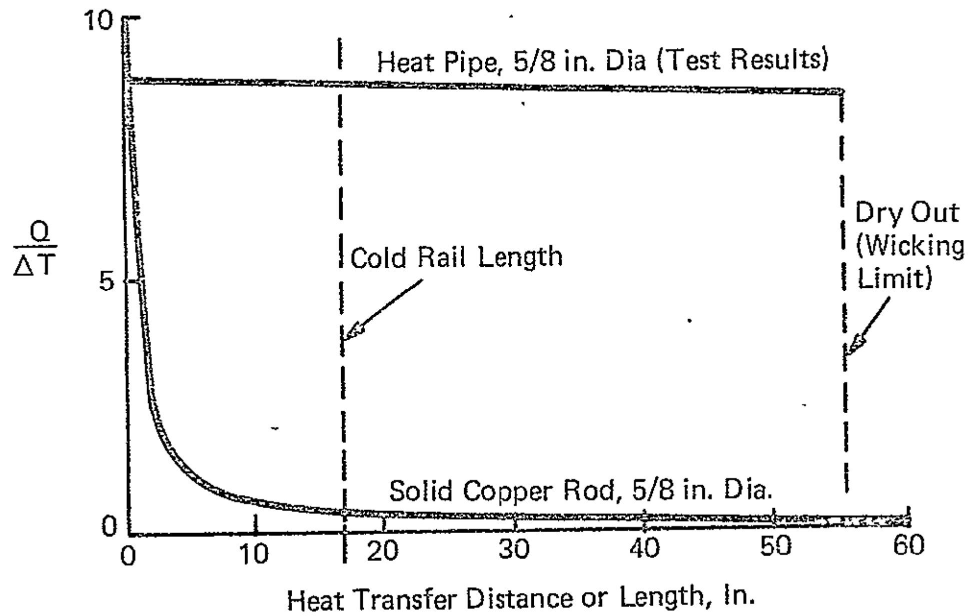
An increase of the fluid film coefficient was attempted by increasing internal fluid flow velocity, but a review of the Lunar Module Environmental Control System data showed the thermal coefficient improvement versus flow for small pump systems to be small and resulted in significant coolant pump penalties.

Attempts to increase the effective coolant-wetted surface by improving heat flow spreading ability and by using thicker rail structure only lead to heavier, undesirable rail designs. Implementation of an isothermal heat pipe was then indicated. The typical function of a heat pipe element is explained in the schematic of Figure 6-18. A general comparison of its expected weight advantages, as compared to a thicker solid rail, can be seen in Figure 6-19.



NOTE: Heat is added in the evaporator causing a change of phase from liquid to vapor of the working fluid. The vapor travels to the condenser where it changes from a vapor to liquid giving up its heat. The liquid is returned to tne evaporator by capillary action in the wicking material. In a basic heat transport device the predominant effect is the ability of the wick to return the liquid to the evaporator, thereby limiting Q (heat transfer rate) and length. In an Isothermalizer the principle concern is to minimize the temperature difference between evaporator and condenser, generally well below max Q. In an isothermalizer there may be the additional complication of several heat sinks and heat sources interchangeable under different conditions.

Figure 6-18. HEAT PIPE SCHEMATIC



Note: The conductance of a heat pipe is several times the conductance of the same diameter copper rod. The heat pipe will have constant conductance with length up to dryout, and then conductance will drop sharply. Dryout is a measure of ability of the wick to transport liquid from the condenser to the evaporator, and is directly related to Q and length of pipe. A weight saving of 80% is also obtained.

Figure 6-19. CONDUCTANCE COMPARISON

The heat pipe serves as an effective method of spreading the localized heat flux laterally along the rail, thus utilizing a greater surface of the rails' internal coolant passages. The schematic of Figure 6-20 illustrates the expected heat flow patterns.

An evaluation showed the heat pipe requirement to be about 20 watts in each direction. The capacity of these pipes is a function of their particular design parameters, which at the present time are many and rapidly varying. Figure 6-21 shows some typical performance data obtained from recent Grumman heat pipe study programs. Although the levels shown in this curve are approximately suitable for our application, they are for a 34-inch long pipe and should improve substantially for shorter lengths.

6.3.4 DC-DC Converter

Figure 6-5 shows the five modules making up a functional one Kw DC-DC Converter assembly. Total power dissipation for the one Kw assembly size is 92.3 watts.

The form factor adapted for these assemblies is the same as that utilized for the Single Phase Inverter design. The Power Transfer Module, which dissipates 77 watts in a 3.60-inch width module, is the thermally pacing unit in this assembly. In spite of a power dissipation density of 0.83 w/in.^{3}, which is lower than the Inverter Power Switch Assembly dissipation of 3.2 w/in.^{3}, this module poses a unique internal design problem.

In order to minimize the requirement for thermal conductor plate thickness and thus optimize the weight, the conduction equation (1) requires that the heat flow path (L), from the maximum dissipation components to the coolant, be minimized to the most practical level. These components are CR1 and CR2 dissipating 20 and 27.5 watts, respectively, and the three power transistors at 9.2 watts each.

Figure 6-7 shows a desirable layout for these components with a representation of expected heat flows. Because of this arrangement, however, the external heat flow to the coolant interface becomes unequal; i.e., the heat flow rejected from each mounting flange is not the same. Heat rejection from the bottom flange was estimated at 52 watts, while only 25 watts was expected at the opposite flange. This would be reflected in higher bottom surface temperatures and, subsequently, a less efficient weight-to-ΔT design unless the component plate and module frame for this side are thickened.

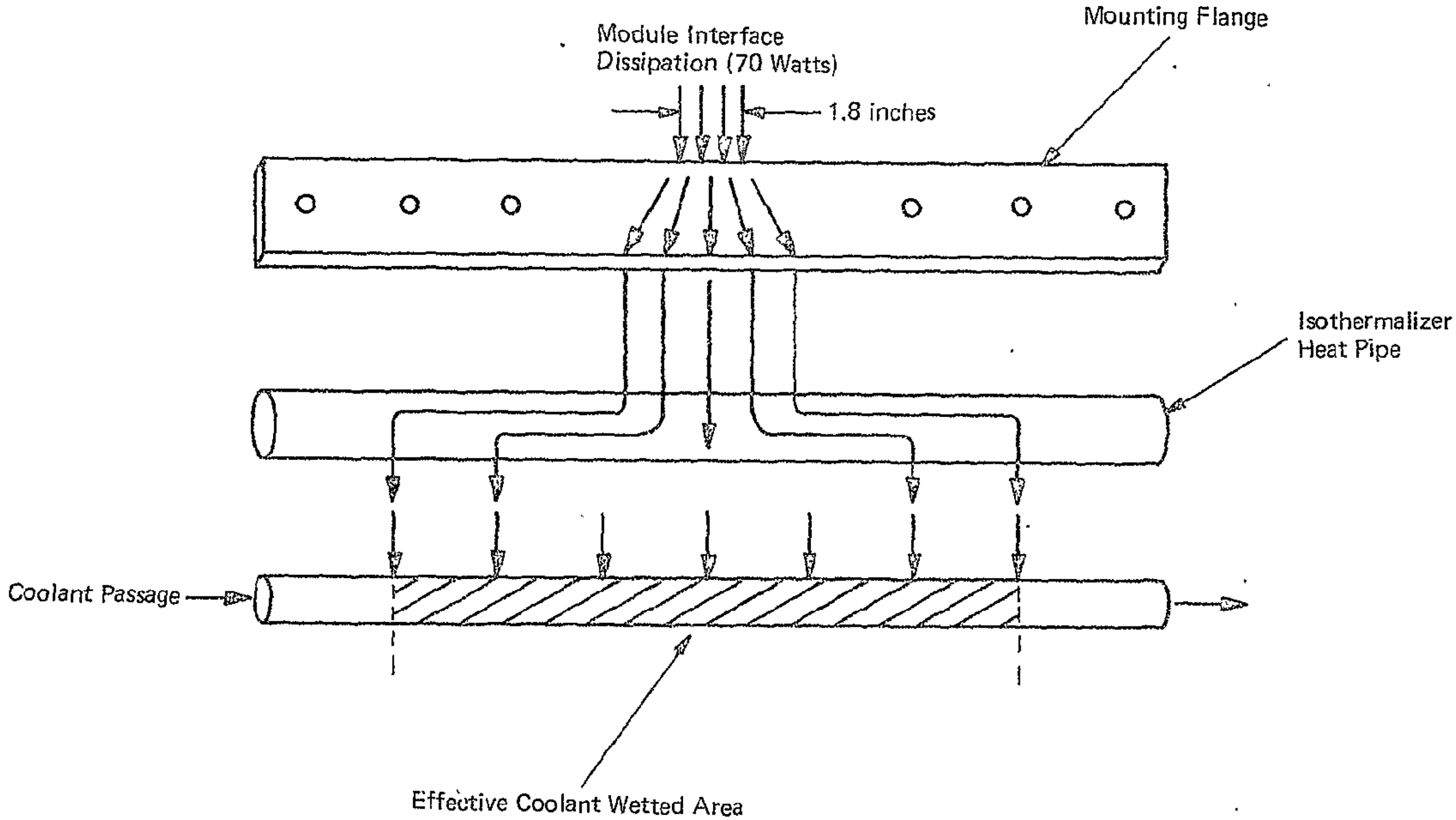
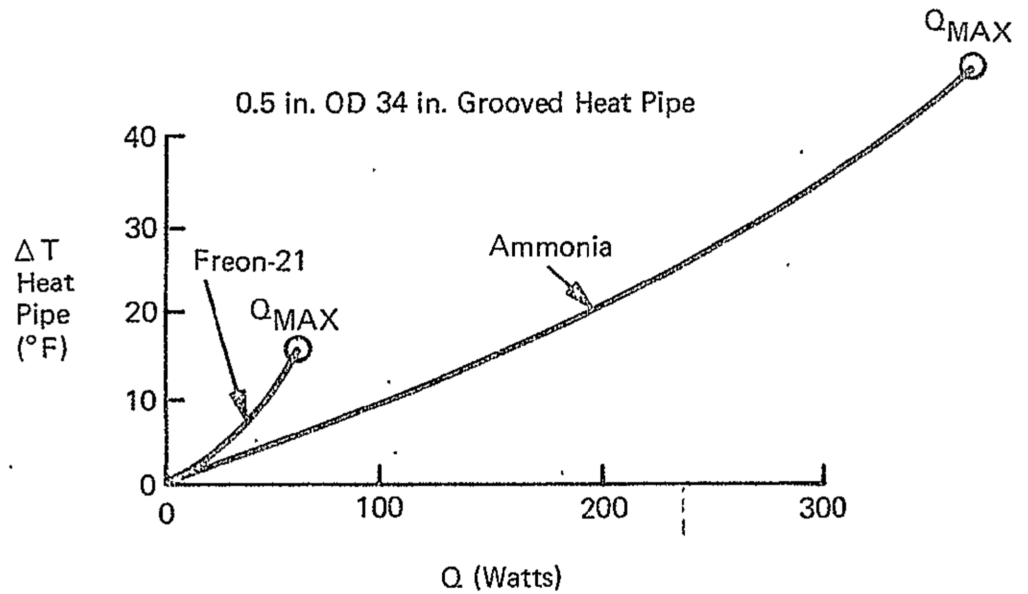


Figure 6-20. HEAT FLOW FUNCTIONAL SCHEMATIC, HEAT PIPE - COLD RAIL



NOTE: In most spacecraft applications, heat pipe thermal transport capacity is limited by the available capillary pumping head. Maximum transport capacity is a function of fluid properties and wick geometry. Data shown illustrate maximum transport capacity for the same wick geometry, but for two different working fluids in a typical heat pipe.

Figure 6-21. MAXIMUM HEAT TRANSPORT CAPACITY - Q_{MAX}

This design would result in a coolant rail interface dissipation of 13.9 watts/linear inch which, although within the design requirement for the cold rail sized for the Power Switch Module, does increase the total load per rail for the lower rail. Since this increases the Environmental Control System cold rail requirements (refer to Section 6.3.3) in addition to requiring an asymmetrical module frame and plate design, it was considered undesirable and an isothermalized plate approach was recommended.

This plate design utilizes a small set of heat pipes (Reference 24) which, by their inherent function (Figure 6-18), prevent an end-to-end temperature difference from existing. These pipes pump the unbalanced heat dissipation from the bottom side location to the opposite flange at a ΔT of approximately zero. In doing this, the heat dissipation is balanced and the coolant interface dissipation is lowered from the 13.9 watts/linear inch to an acceptable level of 10.2 watts/linear inch, resulting in lower overall temperatures. In addition, the pipes' isothermalizing function provides a thermal shunt across the center of the mounting plate, further improving the individual component heat flow and reducing the temperature rise of the power transistors. The curve and explanation on Figure 6-19 shows the relative advantage in weight and performance for a typical heat pipe as investigated in a separate Grumman study.

The capacity of each heat pipe is estimated at approximately 13 watts and is considered to be within present heat pipe technology. The heat pipe orientation has been integrated with the design to provide a desirable gravity direction. Zero "g" operation requires adequate internal heat pipe liquid wicking and is of major concern during a heat pipe design phase.

6.3.5 25 KVA, 3 Phase Cycloconverter

The 25 KVA, 3 Phase Cycloconverter is made up of some of the standard modules previously discussed with the addition of a Power Switch Bank Assembly. Figures 5-2 and 6-10 show the configuration, quantities, and power dissipation levels considered.

A thermal evaluation of all modules, with the exception of the Power Switch Bank, showed that the interface dissipation density using a center flange-type packaging (approximately 2.8 watts/linear inch) to be well within reasonable levels. These assemblies can be suitably cooled with the standard twin-coolant passage cold rail. Because there is no concentration of high heat-loaded areas, such as in the Power Switch Module of the Single Phase Inverter, it is not necessary to employ a heat pipe in these cold rails.

The Power Switching Bank, however, represents an extremely high power dissipation and requires special consideration. In addition to this high dissipation, 670 watts or 1.9 watts/in.^{3}, this unit contains exceptionally high local dissipations. As shown in Figure 6-10, the 12 silicon-controlled rectifiers dissipate about 55 watts each, two inductors dissipate 3.5 watts each, and six fuses dissipate 1/4 watt each. The inductors and fuses represented a secondary problem, while the 55-watt SCRs make it mandatory that these components be located as close to the cooled interface as possible. Thermal analysis shows that series heat flow paths from these SCRs to the cooled interface cannot be tolerated unless extremely large conductor plate thicknesses are employed. Internal heat pipes were considered for this application but are presently incapable of these capacities within the size and gravity vector constraints.

The design established places all the SCR's dissipations in parallel and within 1.1 inches of the cooled interface. Other components are located at somewhat greater distances, but are adequately coupled for their respective low power levels. Figure 6-22 depicts a thermal resistance network analogy of the typical thermal design and shows the expected temperature gradients and couplings.

As shown, this analysis predicts the SCR junction temperature within a reasonable temperature range. Further design refinements will require a detailed weight-versus-conductivity improvement evaluation for each of the effective network resistances. In addition, a final thermal analysis should include a total unit network integrating all the SCRs and including the other internal components.

Compatible external cooling for this design requires a change from the cold rail to a cold plate approach. The change was necessary to provide the smallest thermal path to each SCR. In comparison, the 670-watt split between two cold rails would impose a 335-watt total load requirement and would necessitate designing a heavier, higher capacity cold rail section.

Sample Calculations

$R1 = \theta_{jc} = 0.35°C/Watt = 0.63°F/Watt$ (Vendor Supplied)

$$R2 = \frac{1}{hA} = \frac{1}{6.9 \times 1} = 0.14°F/Watt$$

where:
- h = Interface Conductance, 1000 Btu/Hr-Ft-°F
- A = 1.0 in.^{2}

$$R3 = \frac{L}{kA} = \frac{1.125}{3.1(0.450)} = 0.80°F/Watt$$

where:
- k = Conductivity of material (6101 Al Aly) = 3.1 W/°F/in./in.^{2}
- A = Conductor Cross-section (Effective) = 1.5X0.30 = 0.450 in.^{2}
- L = Conductor Length = 1.125 in.

$$R4 = \frac{L}{kA} = \frac{0.750}{3.1(.218)} = 1.10°F/Watt$$

where:
- k = 3.1 W/°F/in./in.^{2}
- A = .125(1.750) = .218 in.^{2}
- L = .750 in.

= 100°F (Avg)

$$\Sigma R4 \text{ (two in parallel)} = \frac{1.10}{2} = .55°F/Watt$$

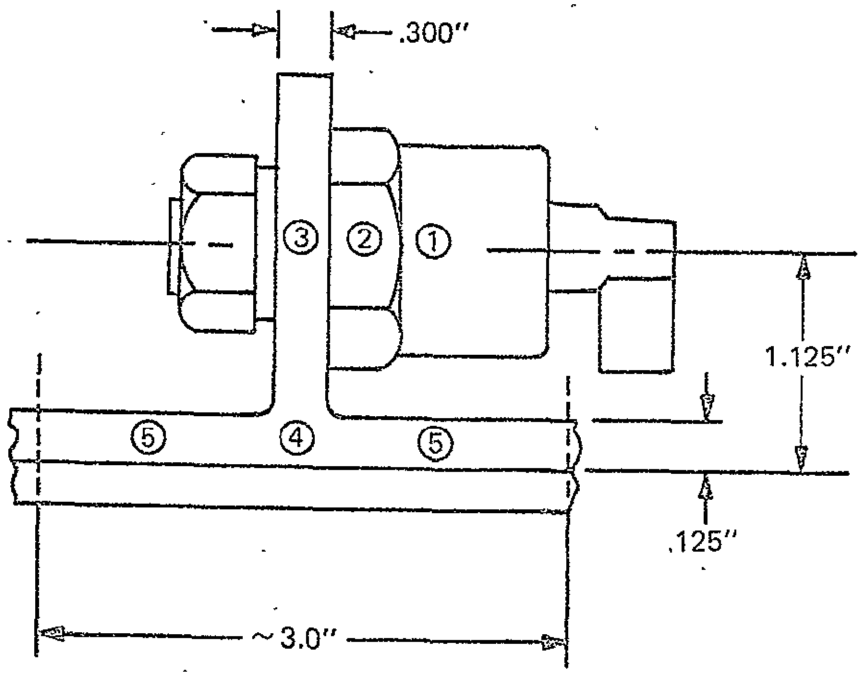
$$R5 = 1.7°F/W/in.^2 \times \frac{1}{2.63} = .64°F/Watt$$

where:
- A = Base area of each base node = 1.5 X 1.75 = 2.62 in.^{2}

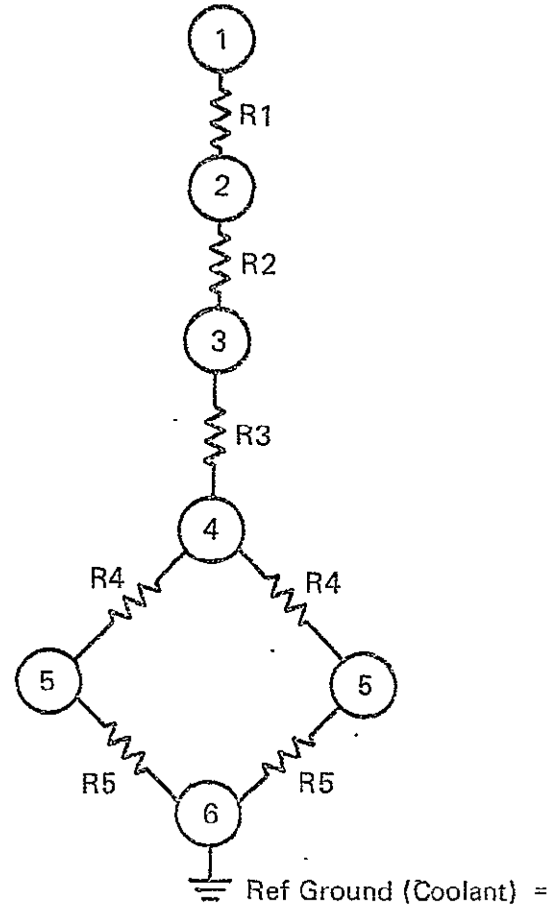
$$\Sigma R5 \text{ (two in parallel)} = \frac{.64}{2} = .32°F/Watt$$

oints (2)

Figure 6-22. THERMAL NETWORK ANALOGY, CYCLOCONVERTER - POWER SWITCH MODULE



Typical Section Schematic



Node	°F Rise	Total Temp
①	34.6	234.1
②	7.7	199.5
③	44.0	191.8
④	30.2	147.8
⑤	17.6	117.6
⑥	--	100.0

Coupling	Value, °F/W	Ident
R1	0.63	Junction to Case (θ_{jc})
R2	0.14	Interface, Component to Thermal Plate
R3	0.80	Down Thermal Plate Rib
R4	1.10	Rib to Base Mode Points Each
R5	0.64	Node Points to Coolant Each

Node No.	Ident
①	SCR Junction
②	SCR Case
③	Plate Rib At SCR
④	Plate Rib Base
⑤	Lateral Base Node Point
⑥	Coolant (Average)

The cold plate design considered for this application is of the .125 in. cross-section typical of the aluminum honeycomb Lunar Module designs. The weight penalty per watt is predicted at .001 lb/watt and the estimated coolant required is 110 lb/hr at $90^{\circ}F$ inlet water temperature.

Analysis of the expected temperature rise for an interface resistance (module base-to-cold plate coolant) of $1.7^{\circ}F/watt/in.^2$ was taken from the LM Program. This value, based on research data provided in Section 5.2, is dependent on a uniform interface pressure and flatness. Because of the large size of the module base and the expected waviness of the flat cold plate, a suitable method of module attachment is important. The quick-release mechanism, as presently shown, is considered deficient in this respect and requires further investigation and development.

The thermal design configuration employed for the Power Switch Module is considered suitable for any application where the primary problem is a large number of very high dissipation components.

6.4 HUMAN FACTORS CONSIDERATIONS

The electrical power assemblies are designed for ease of on-board maintenance. The maintenance task involves principally the replacement of optimum modules. The equipment is designed for easy maintenance under the worst-case conditions, which are as follows:

- Only a single astronaut will be involved in the entire activity.
- The spacecraft will be in a zero-g condition, i.e., not rotating so as to produce artificial gravity.
- The cabin containing the power assemblies has become depressurized, requiring the astronaut to wear a fully pressurized space suit.

The human factors literature was reviewed to supply recommendations in the following areas:

- Tethering techniques
- Handhold design
- Fasteners and tools

The physical limitations of the astronaut in a pressurized space suit are obtained from References 8 and 9. These documents present the mobility limits of the astronaut in the modified A7L (Apollo) spacesuit (Reference 8) and in the advanced extra-vehicular spacesuit (Reference 9). The documents present typical spacesuit reach envelopes and extravehicular glove assembly information, such as dimensions, dexterity, torquing capabilities, and thermal capabilities.

6.4.1 Tethering Technique

In order to remove a module from the equipment rack, the astronaut must be tethered in a position close to the rack so that he can use both hands for the task. A recommended restraint system is described in Reference 10. It consists of (a) a waist tether belt with two D-ring slides worn by the astronaut (Figure 6-23) and (b) two tethers which attach to the D-rings with spring clips (Figure 6-24). The other end of the tethers can be attached to fixed rings near the bottom of the rack or floor. By adjusting the tether length to provide a force component downward, the astronaut can restrain himself for successful performance of the module removal task.

The waist tether was evaluated favorably by astronaut Buzz Aldrin during the Gemini XII EVA activity (Reference 11). Aldrin commented that the use of the waist tether eliminated the constant concern about drifting into an unknown and uncontrolled body position, and allowed the pilot to concentrate directly on the task to be performed.

6.4.2 Handhold Design

Even with the restraint system described above, handholds are recommended on the equipment rack. U-bar handles are recommended. A suggested configuration is shown in Reference 12. The dimensions illustrated are as follows:

- Optimum diameter: 1 inch
- Distance between centerlines of legs: 5-1/2 inches
- Distance from centerline of handle to console: 3 inches

6.4.3 Fasteners and Tools

Costick (Reference 13) states that, in considering the problems of maintenance in space, two types of force application will be prevalent; torque (or rotational) and linear

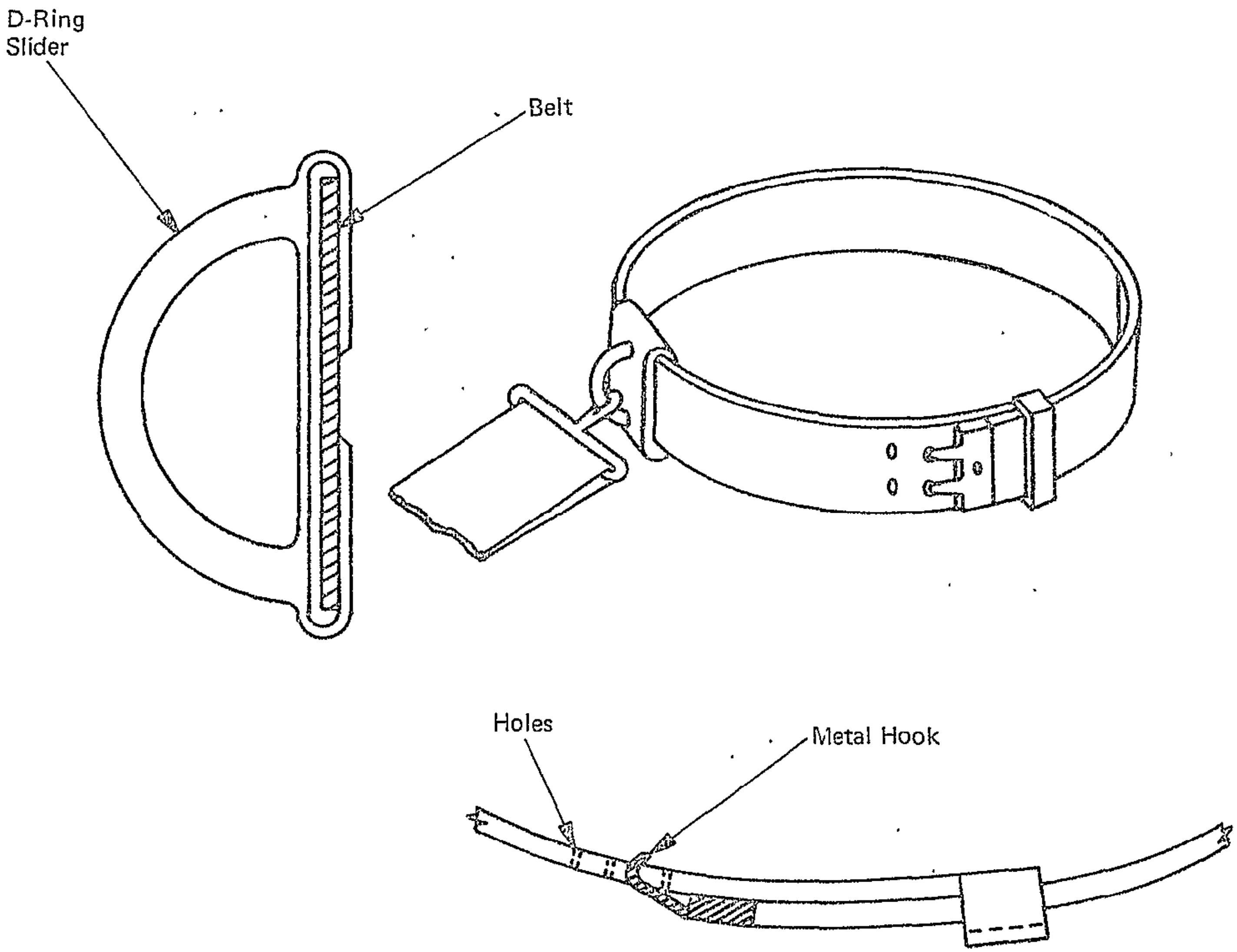


Figure 6-23. WAIST TETHER BELT

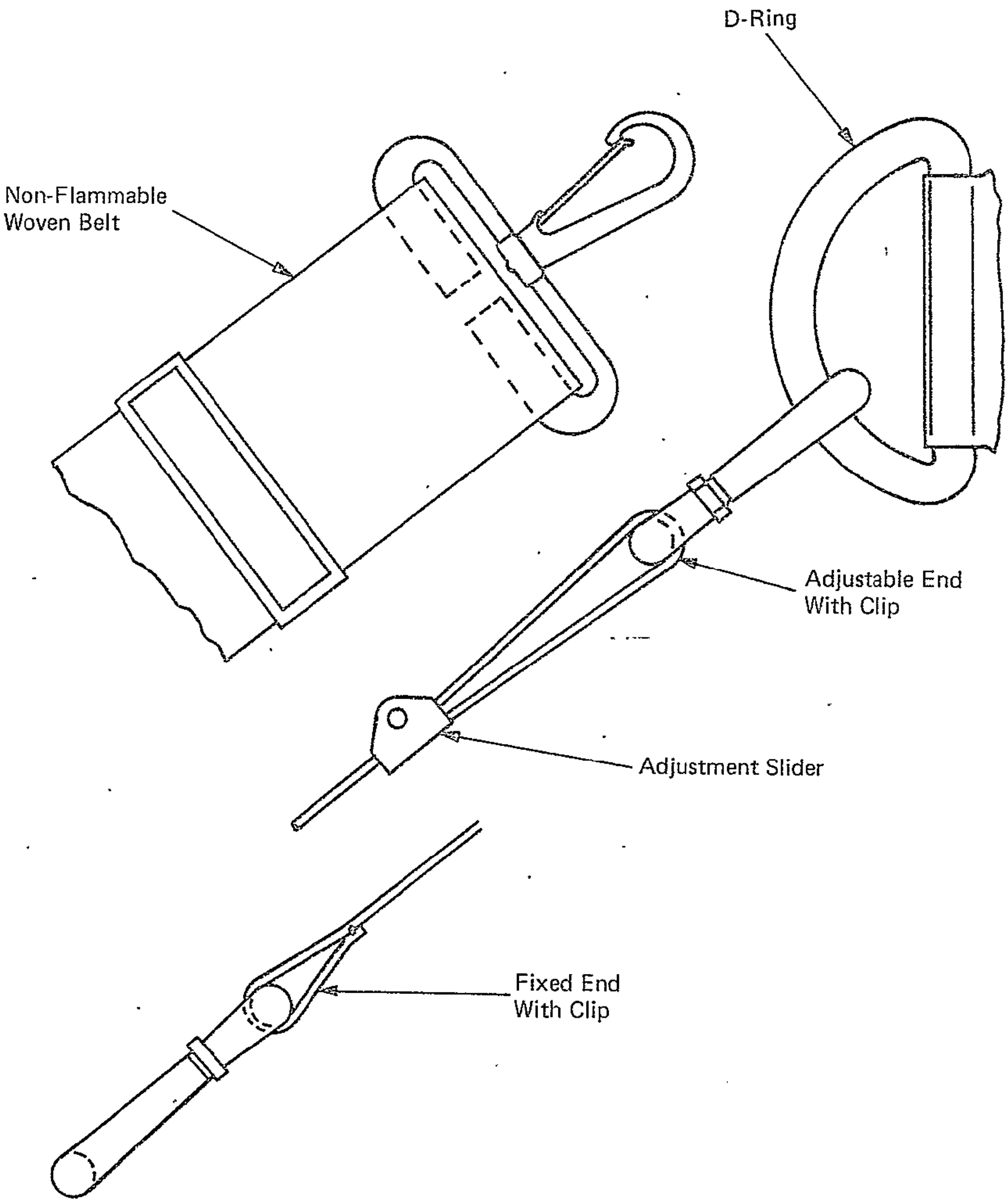


Figure 6-24. FLEXIBLE WAIST TETHER

(or push-pull) forces. The application of torque in a weightless state creates a reactive force which tends to rotate the astronaut. Tethering can solve this problem. Costick states that it is absolutely essential that no axial end loading be required for operating fasteners. The problem of push-off can be avoided by using bolts which require wrench operation, rather than screws which require screwdriver operation. In addition, slotted screws have a tendency to become damaged with use. The damaged screw head required an even greater axial end loading force to remove it than when undamaged, thus compounding the problem.

A hexagonal-head bolt with fine threads is indicated for high torque useages (Reference 14). In the installation, the bolt head is followed by a split-ring lockwasher and then a flat washer. All three, the bolt, lockwasher, and flat washer, are captive to the module by threading the module hole (Reference 14, page 64). A threaded nut plate (Reference 15), which will serve a series of adjacent modules, is recommended. The nut plate is not permanently attached to the cold rail, but can be removed if all the modules bolted to it are removed. Thus, a module can be removed without someone holding the nut or catching the nut after the bolt is withdrawn from it.

With this arrangement, maximum compression of the module to the cold rail is attainable and no loose parts (bolt, washers, or nuts) are present. Also, if any of these parts become damaged, they can be easily replaced.

Schwinghamer (Reference 16) states that, from the results of preliminary neutral buoyancy simulation studies of tool performance, ordinary hand tools are more adaptable and valuable than expected at first. The use of a socket wrench, extension, and ratchet was evaluated by (a) a scuba diver under water and (b) an engineer in an Apollo-type spacesuit with no immersion. No problem was reported with the use of the tool in either case.

The socket wrench and ratchet tool was evaluated during the Gemini XII extra-vehicular activity (Reference 11). Buzz Aldrin stated that he had a problem with the ratchet. The friction in the ratchet was too high in comparison to the loosened bolt. Hence the tool would not ratchet after the bolt was loosened. This problem can probably be corrected. If not, the ratchet tool must then be used as an ordinary fixed wrench after the bolt is loosened and before it is finally tightened. Aldrin had no other unfavorable comment to make about the ratchet operation.

Wortz (Reference 17) reports that the principal disadvantage of the socket wrenches used in their underwater simulation tests was the inadvertent disconnection of the tool. With the proper selection of socket sets, however, this problem probably can be corrected. Wortz concludes that, when the subject had a good steady position, the T-socket and the ratchet wrench worked as well as any combination of wrenches tested.

Therefore, the socket wrench, extension, and ratchet tool are recommended for loosening the hexagonal-head bolts attaching the module to the rack. Since it is a standard tool, it can be used in many other maintenance applications aboard the space vehicle.

6.5 VOLUME VERSUS POWER OUTPUT

In the course of the design study, the relationship between the equipment power output and its volume was investigated.

Preliminary design layouts were made of larger capacity equipment that would still fit into the standard vehicle rack. The component volumes were scaled up using the following relationships:

For magnetics, $$\frac{V_2}{V_1} = \left(\frac{KW_2}{KW_1}\right)^{0.625} \quad (1)$$

where V = Volume of inductors or transformers

KW = Power rating

For capacitors, $$\frac{V_{C2}}{V_{C1}} = 0.9\left(\frac{V_2}{V_1}\right) \quad (2)$$

where V_C = Volume of capacitors

V_2/V_1 = Ratio of magnetic volumes from (1)

The Single-Phase Inverter Filter Module requirements increase from about one to approximately three modules as the power output goes from one to ten kilowatts. The volume of the Power Switch Module varies directly as the power output, while the number of Power Drive Modules increases from one to seven as the power rating goes from one to ten kilowatts. Four modules - the Bias Supply, Reference Oscillator, Reference Voltage

Detector Amplifier, and Programming - do not change in volume with an increase in power rating. Figure 6-25 shows the separate effect of the control modules and the Power Switch and Filter Modules.

Extrapolations were also made of the sizes of the DC-DC Converter to two and ten kilowatt sizes. Plots were also made for Cycloconverters of ten and fifteen kilowatt sizes. These are shown in Figures 6-26 and 6-27.

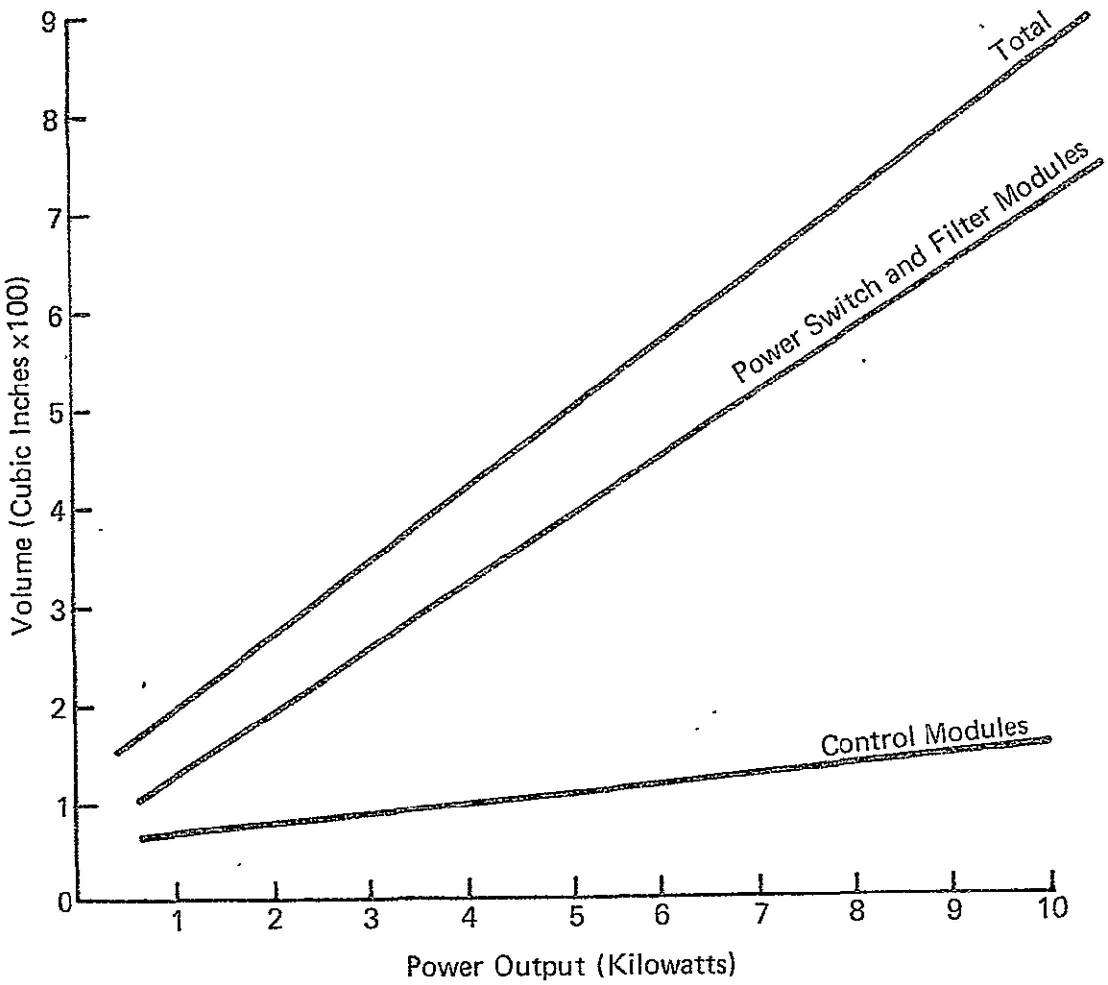


Figure 6-25. VOLUME VS POWER OUTPUT, SINGLE PHASE INVERTER

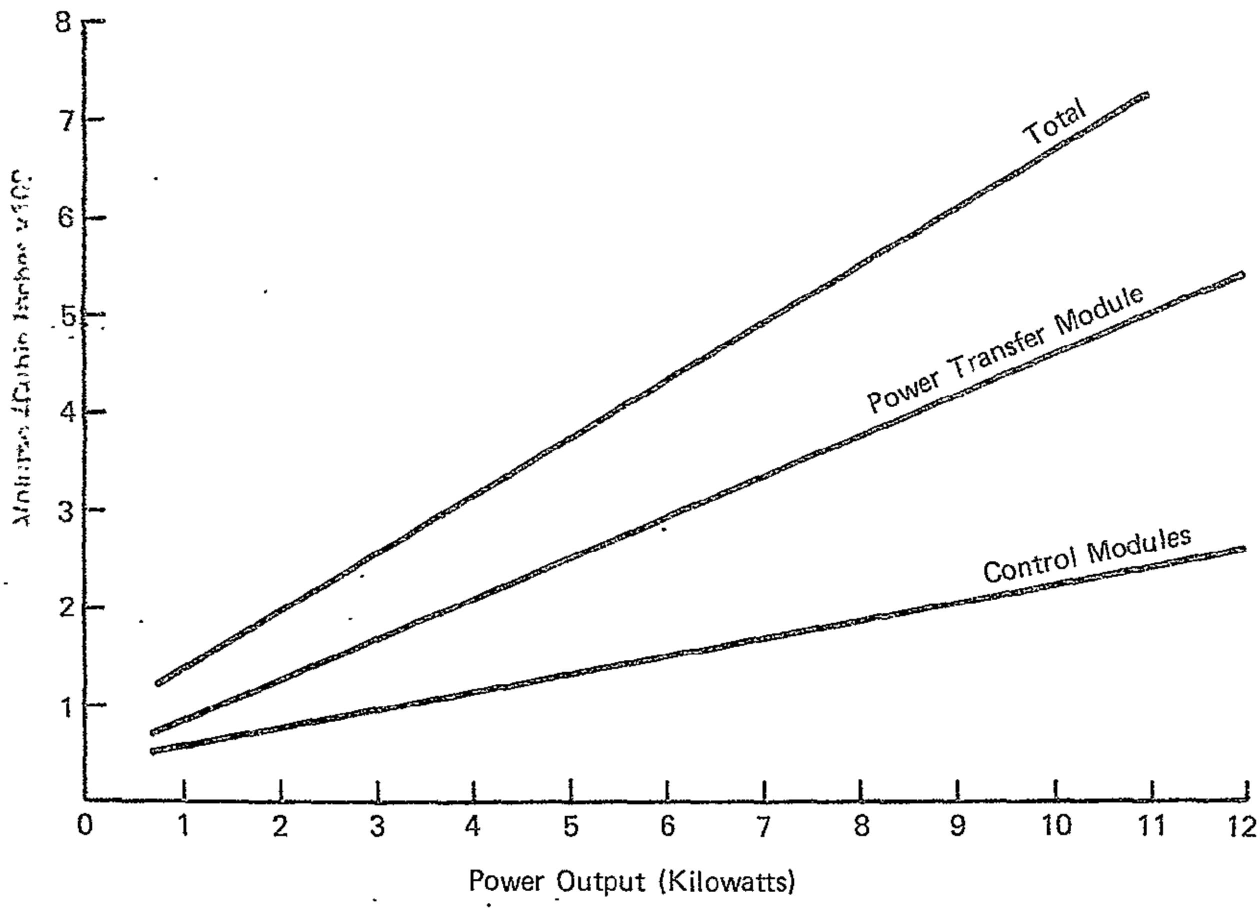


Figure 6-26. VOLUME VS POWER OUTPUT, DC-DC CONVERTER

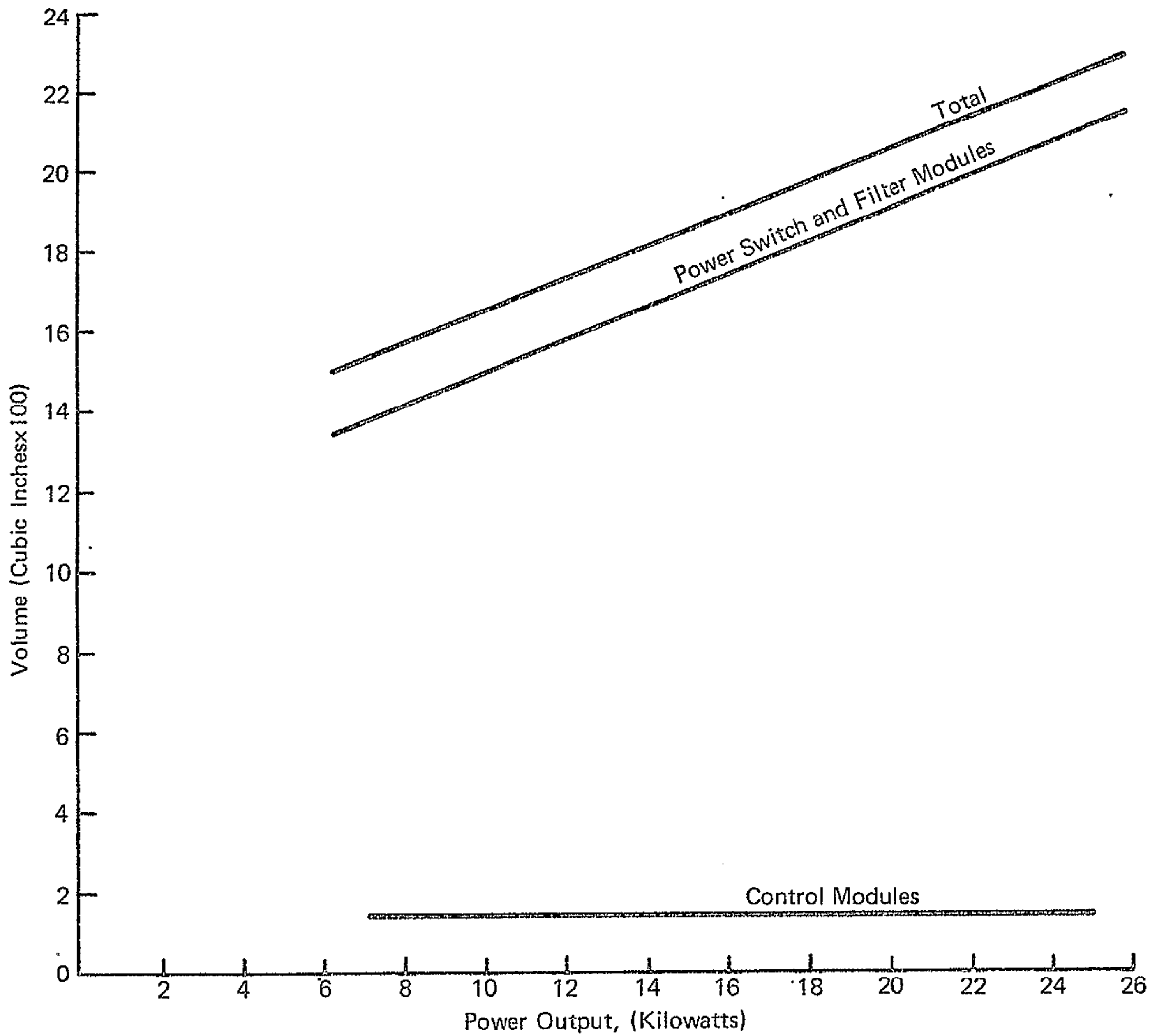


Figure 6-27. VOLUME VS POWER OUTPUT, CYCLOCONVERTER-3 PHASE

SECTION 7

DESIGN CRITERIA

7.1 DESIGN CRITERIA - SPECIFIC

7.1.1 Mechanical

- Make equipment of the lightest weight consistent with sturdiness, safety, and reliability.
- Hardware such as covers, connectors, or doors must be keyed or shaped for installation in the correct position only.
- Make identification markings permanent and legible.
- Lift points must be positively identified and marked. Instructions must be permanently marked on the unit when sequential assembly or disassembly of the unit is required.
- Removable closures, plugs, and small covers should be permanently attached to prevent loss.
- All connectors must be keyed.
- Package control and logic circuitry (including bias supplies) in unit width (.60 in.) modules.
- Package power controllers, including current sensors, in unit widths for low rating ($\sim$ 1 amp) and increasing widths for high ratings. Power dissipation per controller should be approximately

  - DC: 0.5 watt/rated ampere to 50 amp
  - AC: 1.5 watt/rated ampere to 35 amp

  Above these ratings, a hybrid system in which contactors are driven by control electronics is recommended. Hybrid devices can also be packaged in accordance with the technology developed in this study.

- Include assembly instructions (cautions, tools, potting, etc.).

- The standardized functional modular approach lends itself to easy maintainability regardless of the size of the power assembly. Integration is simplified since no special trimming is required in this process. This approach also enables trade-offs of subsystem and system configurations to be made readily, since standard data is used. Finally, system performance predictions are relatively easily derived.

- Provide space for two dual-in-line package integrated circuits for built-in test. One is to detect the critical parameters, and the other to provide the failure signal.

7.1.2 Thermal

- To reflect reliability goals for long-time space use, limit component temperatures as follows:

  - Solid-state power device junctions: 212°F max
  - Resistors, capacitors, chokes, and transformers: 160°F max. at part surface
  - Integrated circuits, flat packs, or DIPs: 190°F at junction

- Consider cold rails with heat pipe isothermalizers for heat dissipations over 8 watts/linear inch.

- To provide a reliable and predictable interface conductance under vacuum or high heat flow density conditions, maintain a high and uniform pressure, approximately 20 psi, at all heat sink joints. Use an unloaded silicone grease or other suitable interface material.

- To minimize Environmental Control/Life Support System penalties, maintain coolant temperature requirement at 90°F or higher.

- Provide the lowest possible thermal resistance in heat flow paths. Conductive members should be short, have large cross-sections, and be made of metals having good thermal conductivity.

- All power handling semiconductors should be mounted on metallic conduction members or sinks. Where electrical insulation is required, it must not produce unsound thermal designs. Investigate the use of BeO as an insulation with outstanding thermal conductance characteristics.

7.1.3 Electrical

- Design equipment to give proper operation over a range of 90 to 110% of nominal power line voltage and 95 and 105% of nominal power line frequency.
- Design equipment to withstand power line voltage and frequency transients.
- Adequate derating in parts application must be used in order to increase reliability of equipment in service.

7.1.4 Maintainability/Human Factors

- All fault repairs are to be accomplished by remove/replace of modules as the replaceable elements.
- Equipment design must make allowances for replacement while wearing protective suits, restrictive gloves, and helmet.
- All replaceable units are to be designed for remove/replace action to be performed by one crewman using one hand.
- All replaceable units must have mechanical keying provisions to prevent improper installation.
- All replaceable unit installations must have quick and easy mechanical alignment and visual orientation to assist the astronaut during replacement.
- Units shall be small and light enough for one man to handle and carry. Weight of removable units shall be held below 30 pounds.
- All replaceable units must have provisions for handling during installation and removal operations.
- Use quick-opening fasteners (one turn maximum) for equipments which must be serviced frequently.

- Interface materials requiring no cure should be used where easy removal or interface separation is required.
- Provide test points for checking essential voltages and waveforms and for injecting signals. All test points must be readily accessible when equipment is in its service position.
- Service instructions should be mounted on the equipment and be designed to last the equipment life.
- Part reference designations should be located adjacent to each part.
- Color-code wiring in accordance with standards.
- Transformers, chokes, and potted networks should have circuit diagrams with current, voltage, and impedance ratings permanently marked on the outside.
- Mark transmission line terminals with the characteristic impedance of the line.

7.1.5 Safety

- Leakage current levels must remain below 3 ma for DC and 0.75 ma for 60 Hz. Thus, insulation resistance to man-available surfaces or handles must be $\geq$ 20 Megohms when measured at 50 VDC or 500 V, 60 Hz. Leakage currents must be measured for 30 minutes at twice the operating voltage plus 250 VDC or 500 V, 60 Hz, whichever is larger. Such current should not exceed the values noted above, and should decrease as time progresses because shock effects are cumulative with time.

  It must also be noted that RMS, 60 Hz voltages are 2.5 to 4 times more dangerous than equivalent DC average values.

- In general, the insulation resistance of a packaged module should be sufficient to withstand one of the following:
  - DC Equipment. 1-minute application of 1000 V or twice operating voltage +250 V, whichever is greater, between any terminal and case. Retest should be done at lower voltages.

AC Equipment Dielectric Test. 1-minute application of 1500V RMS or twice operating voltage +500V, whichever is greater, between any terminal and case. Test frequency can be 60 Hz or 400 Hz, whichever is determined to be more applicable. Retest should be done at lower voltages.

- To avoid both personnel hazards and equipment damage during maintenance, safety interlocks which remove at least input power are mandatory on all assemblies.
- The accumulation of surface charge can result in hazard to both personnel and equipment. The following criteria may be thus derived:
  - All equipment shall show that surface charge is not accumulated on the case during or because of operation in any specified input, output, or environmental condition.
  - All equipment cases shall be grounded to the system single-point ground by a combination of bonding and provision of a ground wire, as required.
  - For docked vehicles, surface charge differential sensing shall be required. A method of dissipating any such charge safely shall also be required.
- No operation of the equipment or system shall cause the occurrence of excessive transients within the system or equipment which may be damaging. In addition, no transient deviation shall be such that personnel hazards may be encountered. MIL-STD-704A transient requirements are a minimum requirement. Equipment requiring lower transients shall be isolated by local power conditioning which includes relay-coil arc suppression.

7.1.6 Materials

- Do not use iron or steel except where required for electromagnetic or strength reasons. Screws, nuts, and studs should be of nonferrous materials.
- Beryllium or beryllium alloys should not be used where machining, forming, or oxide formation can contaminate the cabin environment.

- Do not couple metals that differ in electromotive potential by more than 0.25 volt in the presence of an electrolyte, such as the atmosphere.
- Plate or otherwise treat metals to protect them from corrosion.
- Magnesium should not be used unprotected for long periods of temperatures above $400^{\circ}F$ in a vacuum environment due to its evaporation potential (.004 in./yr).
- Protective coatings should be used to limit evaporation and increase the corrosion resistance of magnesium and its alloys.
- On components requring biological sterilization, only magnesium alloys AZ91C and HK31A should be used.
- Aluminum alloys of the 1100, 3003, and 7075 series should not be used where biological sterilization is required.
- The low melting point metals, gallium and indium, are not compatible with thermal sterilization cycles.

7.2 DESIGN CRITERIA - GENERAL

7.2.1 Mechanical

- Avoid the use of cantilever mounting for parts.
- Loacate heavy parts as close as possible to load-bearing structures and as near as possible to the mounting plane.
- Use alignment pins or similar devices to bear shock and vibrational load between chassis, assemblies, and enclosures. Never depend on electrical connectors and chassis slide assemblies to bear such loads.
- Make allowances for changes in dimensions caused by environmental conditions.
- Provide adequate clearance between components to prevent damage during shock and vibration conditions.
- Equipment mounting hardware should be accessible so equipment can be easily installed without the necessity for removing parts and assemblies.

- Lock screws or their holding devices against loosening.
- Torque requirements should be marked on the unit where torque is critical.
- Do not use rivets for mounting parts which may be subject to replacement or for maintaining electrical continuity.
- Avoid use of self-tapping screws.
- Do not use flathead screws on thin panels.
- Reduce number of types and head sizes of screws. Lengths should be the same wherever possible.
- Seals and gaskets should be designed to prevent damage by tools or abrading action of covers.
- Avoid stress concentrations due to notches, small bend radii, abrupt change of cross-section, etc.
- Route cables so that they need not be bent or twisted sharply or repeatedly.
- Protect wire and cables running through holes in metal partitions from mechanical damage by the use of grommets or other suitable means.
- Stranded copper wire that has been soldered to a terminal must be secured so that vibration does not cause the conductor to flex near the area where the individual strands have been soldered together.
- Do not join leads without a support at their junction.
- Keep solder points away from temperature-sensitive parts.
- Avoid foreign materials and moisture traps in the form of blind holes, corners, or pockets.
- Provide temporary closures to prevent entry of foreign material through openings left when regular covers are removed for shipping, testing, etc.
- Package control and logic circuitry (including bias supplies) in standard unit width modules.

- Units serving the same function in different applications should be interchangeable.
- Provide suitably labeled jacking and hoisting points.
- Package properly to protect equipment during shipment and storage.
- All positive connector pins should be separated from negative pins as much as possible in connector layouts.

7.2.2 Thermal

- Employ a center cold rail configuration as a first choice, since this configuration provides more favorable package density and handling characteristics.
- Where the circuit requires a large number of high-dissipation components in the same package, switch to a flat package configuration to provide parallel path heat flow and a short distance to the heat sink (Figure 6-10).
- Maximize utilization of the more effective conductive heat transfer to improve the weight trade-off.
- Use conductive heat transfer to lower the surface temperature of high power-density devices such as power-handling resistors, semiconductors, and transistors.
- The higher dissipator in a circuit should be located as close to the outer heat sink surface as possible to minimize heat flow rates over longer thermal paths.
- Since temperature rises are additive, distribute dissipators evenly to prevent local hot areas from imposing lower coolant temperature requirements.
- Temperature-sensitive parts should be located away from high heat dissipators and never up stream to the major flow of heat.
- Heat sources should have high emissivity. Use polished or bright plated (low emissivity) shields to protect sensitive parts from radiation from nearby hot parts.
- If dissipation cannot be made uniform, consider internal heat pipes to attain isothermalization efficiently.

- To insure the best utilization of structurally required materials, use a common structural and thermal interface.
- Minimize the number of internal interfaces since they are significant and difficult to control.
- Select conductive materials with a high conductivity-to-density ratio. When stiffness is more important, use magnesium alloys. Use aluminum alloys for strength.
- Avoid a series of dissipating components on the same thermal conductor, unless they have small heat flows, since the temperature rise is an arithmetic sum.
- During the design stage, keep heat flow paths simple to allow pratical design thermal analysis for required trade-offs between other disciplines.
- Where dissipation densities are too high for practical application of forced air or passive techniques, consider active liquid coolant loops for all power conditioning equipment.
- Since a high coolant flow rate is desirable to attain lower component temperatures, but requires more Environmental Control System/Life Support System pump power, a trade-off must be made between coolant work power and weight savings.
- The capability of coolant loops should be known (available flow rates, coolant temperatures).
- Extreme care should be taken for semiconductors (by measurement, if in doubt) to never exceed recommended maximum junction temperatures under any condition of load or thermal environment.
- Design equipment so that heat flow paths are the result of deliberate, considered effort such that the thermal performance may be subject to manufacturing control in the same manner as electrical performance.

7.2.3 Electrical

- Apply all parts with proper concern for environment. Allow for change in value of part parameters with time, temperature, and humidity.
- Reduce stress on parts to improve reliability.
- Do not use any part in an application depending on a parameter which is not controlled by the procurement specification. Do not select any part for tighter control of a parameter than is available in normal procurements.
- Minimize use of parts known to have high failure rates such as connectors and relays.
- Use of flat, aluminum assembly busing is highly recommended as being the lightest and strongest method, but avoid dissimilar metals.
- Internal wiring should utilize flat cable wherever practicable.
- Size wiring and connectors for current and voltage levels carried (Reference 21).
- Check thermal tolerances of components, leads, and conformal coatings.
- If a component has pre-tinned solder leads, make sure that this solder and the installation solder are thermally compatible.
- Provide protection from damage due to overload, excessive heating, etc.
- Verify that tolerance buildups are within the range of adjustment.
- Use limiting resistors in test point circuitry to prevent failure of any component if a test point is grounded.
- Fuse or otherwise protect both sides of the line and provide spare fuses in a convenient location.
- Design equipment so that radio frequency interference and undesired radiations are within specification limits.

- Fault isolation schemes should disconnect both input and output power from a failed assembly.
- General power requirements, including the AC-DC split, should be determined prior to initiating the design.

7.2.4 Maintainability/Human Factors

- Design equipment to be maintained by personnel working under difficult conditions.
- Minimize down time by use of replaceable modular assemblies. Use go/no-go indicators and built-in test equipment where feasible.
- Critical system equipment must be designed to eliminate all requirements for adjustment or alignment as a result of remove/replace action.
- Reduce the number of types of parts required. Utilize common parts where possible. Insure complete interchangeability of all like removable assemblies and parts.
- Wherever possible, handles or grasp areas should be located over the module center of gravity so that the unit does not swing or tilt when lifted.
- Fastening mechanisms should be an integral part of the module or the mounting rails, plate, board, etc.
- Use a minimum number of fasteners for module installation.
- Designs should eliminate the requirements for special tools, but if a tool is necessary a universal and tested type is desirable.
- All replaceable units must have a fast-acting lock-up and release of thermal, electrical, and structural interfaces using a single-motion mechanism, if possible.
- All replaceable unit critical areas such as thermal, structural, and electrical interfaces must be designed for protection from damage as a result of grasping, handling, and carrying.

- The interfaces (thermal, electrical, and structural) of all replaceable units shall be designed to prevent cold welding in space.
- Special test equipment should not be required.
- Provide for the making of crucial adjustments in emergency situations without need for complex associated equipment.
- Mechanical assemblies subject to maintenance disassembly should be indexed to insure proper relative position of parts on reassembly.
- In mounting parts, keep ease of maintenance in mind. Provide access to both sides of chassis. Leave sufficient hand room to remove/replace parts. Provide hand grips for lifting.
- Use care in mounting miniature parts. Their smallness often influences the designer to mount them in ways which make maintenance difficult.
- If certain steps in a maintenance procedure must be performed in an invariant manner, equipment should be designed to permit performance of the steps in that order only.
- Where applicable, use marking and dating for the purpose of age control.
- Standby redundancy is considered a weak method of achieving reliability, since it requires a method of switching the load equipment from one source to the other. Parallel redundancy is preferred, with each power assembly normally operating at partial load. However, this method may decrease system efficiency.
- Identify each module by function, if possible.
- A full-scale mockup of equipment should be prepared, if possible.
- Select vendors whose reliability of performance is proven.
- Simplify designs.
- Use fail-safe designs in those areas where high reliability cannot be expected and the consequences of failure are severe.

7.2.5 Safety

- Excess voltages which last for extended periods may lead to corona losses and/or arc-over.
- Warning indicators should be provided for any hazardous situtation. High temperature, high voltage, or extreme cold indicators should be provided.
- Provide handrails or footrails.
- Safety considerations applied during the design phase are generally superior in concept and operation to those which are applied in the post-design phase.
- Electrical design should eliminate the possibility of cases becoming electrically charged.
- Ground all external metal parts. The length of projecting and overhanging edges should be held to a minimum, and all edges/corners should be rounded.
- Module covers should be considered as an integral part of the rack design to prevent accidental contact with hot modules during normal operation. Use maximum temperature visual indicators.
- Do not locate commonly worked-on parts near unprotected high voltages or hot parts.
- Provide interlocks, with a means of bypassing for servicing, with a proper warning indicator.
- Provide guards, safety covers, and warning plates for potentials in excess of 350 volts rms on contacts, terminals, and like devices.
- Provide voltage dividers with test points for measurement of voltages in excess of 1,000 volts.
- Design the system so that all "hot" connector contacts are socket contacts.
- The machining of beryllium or beryllium alloys should be avoided in manned compartments during all phases of production, test, or flight.

7.2.6 Materials

- Consider the following parameters for selection of metallic materials and finishes:
  - Strength/weight ratio
  - Thermal conductivity/weight ratio
  - Corrosion resistance
  - Coefficient of thermal expansion
  - Machinability
  - Weldability
  - Forms available (castings, extrusions, sheet, etc.)
  - Maximum useable temperature limits
- Select materials such as potting compounds, sealants, lubricants, adhesives, etc. on the basis of:
  - Outgassing
  - Flammability
  - Cure cycles
  - Ease of installation and removal
  - Maximum useable temperature limits
- Avoid threading aluminum alloy into aluminum alloy parts.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The general objectives of this study have been achieved. Design approaches have been made of representative electrical power system assemblies. A list of design criteria has been collected that applies to this and similar equipment.

- The cooling of extreme high power dissipation density modules can be achieved with reasonable size and weight impact.
- High power dissipation at small mounting interface areas can be handled using a thermal heat pipe and cold rail combination.
- High total module power can be handled by standard cold plate applications.
- Lowering coolant temperature can provide greater cooling capacity but it increases the radiation penalty in the environmental control system and is not desirable.
- Modules with large and severely unbalanced internal dissipations can be isothermalized by the application of internal heat pipes.
- Applications in gravity fields of varying direction and intensity require further heat pipe evaluation.
- All module thermal interface mounting configurations can be achieved in three basic designs: twin cold rail, flat cold plate mounting, or twin cold rail-heat pipe mounting.
- Changes in thermal interfaces resulting from system growth in electrical power dissipation output is self-compensating, that is, the use of more modules or large modules results in equal or less coolant interface dissipation density.

- The packaging technology developed by this study are consistent with the design criteria.
- Modular packaging of power assemblies provides opportunities for a low-cost approach through commonality of module enclosures, mounting arrangements, and interchangeability of control modules.

8.2 RECOMMENDATIONS

It is recommanded that the study be continued into the Phase II Design Effort and Breadboard Construction. The Phase II effort consists of the design, fabrication, and evaluation of three main breadboard efforts as follows:

- Internal Thermal Model. The Power Transfer Module of the DC-DC Converter is selected because it is most representative of a typical power assembly with non-uniform thermal dissipation characteristics. The design will utilize internal heat pipes.
- External Thermal Model. This module thermally will represent cold rails, including integral heat pipes, with thermal inputs simulating a standard rack shelf of typical power assembly modules.
- Maintainability/Human Factors Model. This model includes an equipment rack with typical modules to demonstrate the maintainability and human factors aspects of the design.

The Phase I study resulted in the development of an approach to packaging of power assemblies for space applications which promises to be capable of surviving severe environmental conditions and is so versatile as to be readily adaptable to packaging a broad variety of electronic equipments as well. The developed approach, therefore, has the distinct potential of becoming the standard packaging concept for a majority of electrical/electronic equipment for future space vehicles. The Phase II effort will refine and verify the validity of the Phase I approach.

Other related overall areas requiring further study are:

- Physiological effects of shock hazards with regard to the parameters listed in Section 7.1.5. It is recommended that various types of short-haired laboratory animals with physiological reactions similar to man be used for this study. Furthermore, the test program should be jointly controlled by an electrical engineer, with a safety background and some biophysical knowledge, and a biophysicist with knowledge of engineering parameters. This recommendation is based on the fact that data obtained to date (Reference 22) shows little or no agreement among researchers, and is far more qualitative than quantitative. In addition, this data appears to have inconsistencies, particularly between levels causing death by fibrillation or asphyxiation and those causing severe burns, and among definitions applied to actual effects.

A consensus of the various authorities in the physiological shock hazard field are not in agreement regarding specific levels associated with each of the following effects:

- Sensation
- Let-go
- Tetany and/or nerve damage
- Ventricular fibrillation and/or asphyxiation
- Severe burns and/or cardiac arrest

Almost no data is available on the parameters associated with the following:

- Sex (e. g. , female menstruation)
- Exact state of health and/or nature of specific illness (e. g. , common cold)
- Skin condition (soft vs calloused, moist or oily vs dry)
- Fatigue
- Body weight vs musculature and bony structure (i. e., percentage of fatty tissue with respect to bone and fibrous tissue)
- Environment (e. g. , temperature, humidity, pressure, and atmospheric gas composition)

- Exact time duration to move from one effect to another

- AC frequency

- An investigation should be made to determine how to avoid accumulation of surface charge in operating equipment and how to safely dissipate skin surface charge differences between docking vehicles. This is an area in which little work has been done. It involves materials studies of conductive coatings, capacitive transmission through insulators, and the ability to pre-detect skin change differentials prior to actual docking.

SECTION 9

REFERENCES AND BIBLIOGRAPHY

9.1 REFERENCES

Corrosion Protection of Magnesium and Magnesium Alloys, Defense Metals Information Center, Battelle Memorial Institute, DMLC Memorandum 205, 1 June 1965.

This report contains information about numerous methods of protecting magnesium and its alloys against corrosion. Pre-treatments, conversion coatings, paint coatings, and metallic coatings are treated in some detail and other protective coatings are discussed. A special section is devoted to galvanic corrosion.

2. Air Force Structural Metals Handbook, Air Force Materials Laboratory, Wright Patterson Air Force Base, Ohio, AFML-TR-68-115.

This book provides comprehensive information on metallic materials. Individual chapters are provided for each alloy and supplements are added annually. References are provided following each chapter.

3. Handbook of Electronic Packaging, Charles A. Harper, Ed., McGraw-Hill Book Company, 1969.

A complete handbook covering all aspects of electronic packaging. A fairly large section covering materials, especially non-metallic materials, is included.

4. Interface Conductance Investigation of the LEM ERA Flange - Cold Plate Assembly, T. Potenza, Grumman Aircraft Engineering Corporation Thermal Lab Test Report TLTR-65-1, 18 November 1965.

Results of tests performed on simulated modules mounted to LM cold rails are presented. Interface materials tested included indium foil, copper foil, and silicon grease. The bare joints were also tested. All tests were performed in a vacuum. Results of tests performed on bar interfaces with varying bolt fastener torques are also presented. Detailed discussions of test setup, procedure, and results are provided as well as test data and photographs of test apparatus.

5. Handbook of Design Criteria for Microelectronic System Packages, Volume III A, Design Data, Michael A. Merrigan, Hughes Aircraft Company, Fullerton, California, May 1967, AD 655 763

This volume contains design data for reference, as a means of assisting in the implementation of the procedures developed in Volume II, Packaging System Design and Evaluation Procedure. These data include general guidelines for accomplishing tasks and tabulated information to assist in making decisions during system design and evaluation.

Subjects such as ideal package element characteristics, modularization and standardization design guidelines, and existing packaging systems are discussed.

6. NRL Centralized Electronic Control Packaging, D. A. Venn, E. Toth, and J. S. West, Naval Research Laboratory Progress, May 1965.

This report describes the Centralized Electronic Control (CEC) Packaging System in detail. Topics discussed include cooling, cabinet and rack structure, power distribution, modules, and connectors. The developmental work in the area of connectors is of special interest and appears applicable to designs developed in this space packaging study.

7. Navy Systems Design Guidelines Manual - Electronic Packaging, Naval Applied Science Laboratory, Brooklyn, N. Y., May 1967, AD 815 522, NAVMAT P3940.

This manual provides a compendium of complementary approaches developed under the direction of Navy facilities for the organization and construction of electronic systems.

The four packaging systems discussed include: The "Centralized Electronic Control"; the "Electronic Packaging System" or "Integrated Packaging System"; the "Integrated Helicopter Avionics System"; and the "Standard Hardware" or "NAFI" system.

Each of these systems is an advanced packaging technique that has been found optimum for its respective class of electronic equipment.

8. Design and Performance Criteria of the Modified A7L Space Suit and -7 PLSS/SLSS, Manned Spacecraft Center, Crew Systems Division, October 1969.

9. Extravehicular Activity Hardware Design and Performance Criteria, Manned Spacecraft Center, Crew Systems Division, June 12, 1969.

10. Study of Mobility and Restraint Device Concepts for Future Manned Space Systems, Grumman Aerospace Corp., SRP 14S-104, August 1970.

11. Summary of Gemini Extravehicular Activity, MSC-G-R-67-2, MSC, Houston, June 1967.

12. Human Engineering Design Criteria Handbook for Lunar Scientific Equipment, Hamilton Standard, SVHSER 3998, April 3, 1966, Pages 4-21.

13. The Necessity for Development and Use of Fastening Devices with Special Characteristics for Space Use, J. F. Costick, In National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1, 2, 3, 1966.

14. Guide to Integrated System Design For Maintainability, October 1961, ASD Technical Report 61-424.

15. Human Engineering Design Criteria, MSFC-STD-267A, Sept. 23, 1966, Page 380.

16. Tool Experiments for Assembly, Maintenance and Repair in Space, R. J. Schwinghamer, In National Conference on Space Maintenance and Extravehicular Activities, Orlando, Fla., March 1, 2, 3, 1966.

17. Study of Astronaut Capabilities to Perform Extravehicular Maintenance and Assembly Functions in Weightless Conditions, E. C. Wortz et. al., Airesearch Manufacturing Co., NASA CR-859, Sept. 1967.

18. Interface Thermal Contact Resistance Problem in Space Vehicles, Erwin Fried and Frederick A. Costello, ARS Journal, February 1962.

This paper defines the thermal interface problem, reviews literature previously published on the subject, describes the experimental program undertaken, and provides graphical results for both bare specimens and metallic interface materials. A discussion of the results is also included.

19. LEM Engineering Memorandum LMO-520-226, J. Savarese, Grumman Aircraft Engineering Corporation, 5 Jan. 1965.

Results are presented for interface conductance of bare aluminum joints in a vacuum. Results for a brass joint, tested bare and with a silicone vacuum grease interface material, are presented. The thermal resistance of six different interface materials is also given as a function of joint contact pressure.

20. Thermal Joint Conductance in a Vacuum, E. Fried, ASME Paper Number 63-AHGT-18, March 3, 1963.

This paper critically reviews the current state of knowledge on the thermal joint conductance between metal-to-metal surfaces in a vacuum. Experimental results obtained by the author and other investigators are discussed and new experimental results dealing with interstitial filler materials such as high-vacuum silicone grease and elastomers to improve the contact conductance in a vacuum are presented. These experimental results are an extension of those discussed in Reference 18 above. An attempt is made to develop an empirical solution for the prediction of joint conductance.

21. Current-Carrying Capacity of Aerospace Wires, Grumman Aerospace Corp. Adv. Devel. Program.

22. Correlation Chart of Physiological Effects of Shock Hazards, given K. Castle by hand in February, 1970.

23. High Power Frequency Conversion Equipment Program, Final Report, NAS 9-10430, Westinghouse Electric Corp., June, 1970.

24. Heat Pipe Technology and Applications, Grumman Aerospace Corp. Presentation, 1970.

9.2 BIBLIOGRAPHY

Variable Speed Constant Frequency (VSCF) for the Space Shuttle, General Electric Company Report to GAC, February, 1970.

100 Ampere-Hour Nickel-Cadmium Battery Module, Contract NAS 9-11074.

Space Materials Handbook 3rd Ed., John B. Rittenhouse and John B. Singletary, National Aeronautics and Space Administration, 1969, NASA SP-3051.

This handbook provides information on mechanical, physical, and chemical properties and characteristics for a wide variety of metallic and non-metallic materials. The effects of natural and induced environments are appraised. Information on past usage of materials is also provided.

Aluminum Standards and Data 1968-1969, 1st Ed., The Aluminum Association, April, 1968.

General information is provided on aluminum alloys and processing methods. Specific material properties are provided along with dimensions and tolerances of standard shapes.

Electrical Power Subsystem for Space Shuttle Vehicle, "Orbiter", GAC, February, 1970.

Space Station Program Status Report, Electrical Power Subsystem, GAC, Dec., 1969.

Thermal Conductance across Metal Joints, W. J. Graff, Machine Design, September 15, 1960.

An analysis of the thermal joint conductance in terms of dimensionless parameters is presented. Numerous joints of both steel and aluminum were tested with various surface conditions. Most tests were performed in air and no interface materials were used. Therefore, the results presented are of little value to the study. A figure indicating the relation between basic finishing processes and ranges of surface roughness for five different metals is of some interest.

Measurements of Thermal-Contact Conductance Between Dissimilar Metals in a Vacuum, Walter E. Kaspareck, ASME Publication, June 4, 1964.

Measuring apparatus used in experimentally determining the thermal contact conductance of various dissimilar metal joints, in a vacuum, is described. Experimental results were obtained using combinations of 6061T6 Aluminum, Casting Alloy Magnesium AZ91C, and Almag 35, expected to be used in the Saturn program. Surface finishes ranged from 5 to more than 200 μ-inches CLA (center line average) with contact pressures up to 700 newtons/cm^2 (1020 psi). Again, due to the lack of interface materials, this paper has limited applicability.

Designing Equipment for Reliability, R. B. Wilson, American Society of Mechanical Engineers, Paper No. 57-SA-54.

Mechanical Check List: A Key to Reliable Electronic Equipment, H. I. Dwyer, Jr., Electronic Design, Sept. 2, 1959, pp. 176-186.

Suggestions for Designers of Electronic Equipment, U. S. Navy Electronics Laboratory, San Diego 52, California.

Improving Electronic - Equipment Reliability, H. I. Dwyer, Jr., Machine Design, April 16, 1959, pp. 176-186.

Design Check for Airborne Electromechanical Packages, Erich O. Maue, Electromechanical Design, March 1964, pp 31-37.

Vehicle Electronic Design Engineering Manual, Section B, Grumman Aerospace Corp.

Engineering Systems and Procedures S-1002, Engineering Subcontractor Design Review, Grumman Aerospace Corp.

Experimental Evidence of Thermal Resistance at Soldered Joints, M. Michael Yovanovich and M. Tuarze, Journal of Spacecraft and Missiles, Vol 6, No. 7, July 1969.

The results of a series of tests on soldered joints is presented. The interface material is tin and joints were soldered under pressure. Results indicate very high interface conductivity. The applicability of results of this study is limited since

soldered interfaces would be almost impossible to break and replace in a space station environment.

Flat Conductor Cable Manufacture and Installation Techniques, Wilhelm Angele, NASA TMS-53586, Mar. 1967, MSFC, Huntsville, Alabama, N67-11364.

The E.I.A.: Modular Packaging of Spacecraft Electronics, L. L. Behrendt and J. A. Nelson, A70-12579, Electronic Packaging and Production, Vol. 9 pp. 29-30, Oct. 1969.

Electrical Feed-Through Connection for Printed Circuit Boards and Printed Cable, J. F. Blanche, Patent No. 3,430,182, Feb. 25, 1969, NASA Invention N69-27431.

A New DC-DC Converter Design Philosophy, G. E. Burton, Technical Report N70-12291, Nov. 1968, Royal Aircraft Establishment.

Printed Circuit Connectors For Microassemblies, Howard E. Dwan, A0669256, Cinch Mfg. Co., Chicago, Illinois, Feb. 1968.

The LM: Packaging the Radar Assembly, H. G. Frankland, A69-23537, Electronics and Production, Vol. 9 pp. 115-121, Mar. 1969.

Electronic Miniaturized Packaging and Cooling Research, J. Frinot, AD-681826, General Dynamics/Convair, San Diego, California, Mar. 1961.

Packaging Requirements for Optimized Malfunction Isolation By Systematic Substitution, L. R. Greenman, A69-29494, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-5 pp. 499-514, May 1969.

Space Environmental Effects on Materials and Components, Vol. II, Electronic and Mechanical Components, D. J. Hamman and E. M. Wyler, AD 601876, Battelle Memorial Institute, Columbus, Ohio, April 1964.

Flat Cable Transmission Line Component Assemblies for Subsystem Interconnection, George Hansell, Microelectronic Packaging Conference, SAE, June 1969.

Automated Termination and Connector Flat Conductor Cables, Homer E. Henschen and Clifton W. Huffnagle, NEPCON 1969, AMP Incorporated, Harrisburg, Pa.

Packaging and Cooling Problems Associated with Microelectronics Equipment, F. Honnor and M. A. Thomas, A70-12847, Microelectronics and Reliability, Vol. 8 pp. 331-337, Nov. 1969.

Reliable Flat Cable Connector, R. L. Huffman, AD 839317, Martin Marietta Corp., Orlando, Florida, August 1968.

Optimum Mechanical Packaging of Electronic Equipment Program, Aubrey H. Jones, AD 450291, Hughes Aircraft Company Ground Systems, Fullerton, California, August 15, 1964.

Packaging Concepts for Uncased Integrated Circuit Systems, Martin N. Kann, AD 809438, Radiation, Inc., Melbourne, Florida, Feb. 1967.

Packaging Flat-Packs for Spacecraft Applications, L. Katzin, N67-31592, Jet Propulsion Laboratory, Pasadena, California.

Electrical Connector, Bobby W. Kennedy, (Patent Application No. 889247, Nov. 26, 1969) NASA, MSFC, N70-20737.

Applications of Microelectronics to Aerospace Equipment, E. Keonjian and R. C. Davy, AD 851745, Grumman Aerospace Corporation, Bethpage, N.Y., May 13, 1969.

Criteria for Selection of Wire Applications, Vernon Krueger, NASA TN D-4553, Goddard Space Flight Center, Greenbelt, Md., N68-21766.

Reliability Through Packaging Design, R. E. Duehn and F. J. Price, A67-17467, IBM Federal Systems Division, Oswego, New York.

Equipment Design Considerations for Space Environment, S. N. Lehr, L. J. Martire, and V. J. Tronolone, IDEP B2616, Space Technology Laboratories, Inc., Redondo Beach, California, Feb. 1962.

Metals Handbook, Vol. 1, Properties and Selection of Metals, Taylor Lynman Ed., American Society for Metals.

Standard Modules for Avionics Equipment, D. W. Mackiernan, AD 266609, U. S. Naval Air Development Center, Johnsville, Pennsylvania, September 21, 1961.

LEM Engineering Memorandum LMO-510-375, J. Marssdorf, Grumman Aerospace Corporation, Jan. 11, 1966.

A Plan for the Development of a Practical Microminiaturization Technique, I. Martin, IDEP B1807, July 1961.

Handbook of Design Criteria for Microelectronic System Packages, Vol. I, Packaging System Methodology; Vol. II, Packaging System Design and Evaluation Procedure, Michael A. Merrigan, AD 655762, Hughes Aircraft Company, Fullerton, California, May 1967.

Handbook of Design Criteria for Microelectronic System Packages; Volume IIIB, Design Data, Michael A. Merrigan, AD 655764, Hughes Aircraft Company, Fullerton, California, May 1967.

Handbook of Design Criteria for Microelectronic System Packages; Volume IV, Design Example, Michael A. Merrigan, AD 655765, Hughes Aircraft Company, Fullerton, California, May 1967.

High Density Packaging of Electronic Circuit Modules, E. Miller, N69-17328, Report No. FSR-AD8-09-68.1, Nov. 1968, Grumman Aerospace Corp.

Aircraft Flat Conductor Cable Power Feeders, Julian P. Norris, Electrodynamics Technology, Commercial Aircraft Group, The Boeing Company.

Electronic Packaging, General Specification for, J. E. Morrissey, Spec. 6-17-64, LSP-360-002, Grumman Aerospace Corp.

Flexible Electrical Conductors for High Temperature Switch Gear, Lawrence A. Mueller and William E. Snider, N70-23527, NASA TM X-1986, Lewis Research Center, Cleveland, Ohio, April 1970.

Ministick Packaging - A Further Aid to Satellite Reliability, C. F. Noyes, SD0-1444, The Johns Hopkins University Applied Physics Laboratory, Silver Spring, Maryland, September 1, 1966.

Thermal Conductance of Lap-Joints in Vacuum, A. B. Osborn and W. N. Mair, AD 637770, Royal Aircraft Establishment, Feb. 1966.

Technology Feasibility Spacecraft (TFS), Technology Report Volume I, Electronic Packaging, L. Parham, AD 673563, Martin Marietta Corp., Denver, Colorado, Oct. 1967.

Human Engineering Checklist, Dean W. Plath, AD 477288, Autonetics, January 19, 1966.

In-Flight Maintenance Study Final Report, John T. Polhemus, Dec. 1969, Martin Marietta Corp., Denver, Colorado 80701, NASA Contract NAS 9-8144, N70-16700.

Wirecon - A Wire-Connected Modules System, F. L. Rhodges, A67-25275, Symposium Record-Western Electronic Show and Convention, Vol. 7 pp. 7/23-1-7/23-4, 1966.

Packaging Design of Electronic Equipment for Space Application, B. Schechter, IDEP - C7587, Autonetics, October 20, 1965.

Thermal Problems Encountered in the Design of Electronics Packages for Space Applications and Lunar Missions, Allen L. Schmidt, A68-12619, Symposium Record-Western Electronic Show and Convention, Vol. 8 pp. 5/3-1 - 5/3-7, 1967.

Engineering Evaluation of NAFI Standard Hardware Modules, T. Smith, AD 669460, Naval Avionics Facility, Indianapolis, Indiana, Nov. 30, 1967.

Final Report of Engineering Evaluation of NAFI Standard Hardware Modules, T. Smith, N68-29823, Naval Avionics Facility, Indianapolis, Indiana, November 30, 1967.

High Reliability Connective Devices, Gunther Steinberg and Marvin Garrison, AD 653847, United States Army Electronics Command, Fort Monmouth, N.J., June 1967.

Reliable Electrical Connectors Micro-Circuit Fabrication, W. G. Tait, IDEP D2015, FH-SESD, May 7, 1969.

The Design of Modular Telemetry Transmitters for Satellite Applications, T. Thompson, AD 652806, Johns Hopkins University, Silver Spring, Maryland, March 1967..

Corrosion Protection of Magnesium and Magnesium Alloys, E. L. White and F. W. Fink, DMIC Memorandum 205, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio 43201, June 1, 1965.

Guidelines and Constraints Document Space Station Program Definition Phase B, Harle Vogel, MSC-00141 Rev. H. Manned Spacecraft Center, Houston, Texas, Dec. 12, 1969.

A Study of Electronic Packages, Environmental Control Systems, and Vehicle Thermal Systems Integration. D. J. Watanabe, N67-37649, Contract NAS 8-20320, July 21, 1967, North American Aviation Inc., Space Division.

Advanced Electronic Packaging Techniques, IDEP B7831, Boeing Company, 27 March 1964.

Critical Component Parts in Space Power Equipment, IDEP C2706, Engineering Magnetics, 14 Jan. 1966.

Introduction to the Design and Application of Micromodules, IDEP 347 23.00.00-04-02, Radio Corporation of America, September 1963.

Microelectronics Engineering, Design Fabrication, Materials, Packaging, AD 652388, U. S. Naval Avionics Facility, Indianapolis, Indiana, 1 January 1965.

NRL Modular Electronic Packaging, AD 693097, Naval Research Lab, Washington D. C., May 1967.

Space Handbook, AD 821840, Warfare Systems School, Air University, Maxwell Air Force Base, Alabama, 31 Oct. 1967.

Study of Electronic Packaging Standardization Concepts, AD 861329, Naval Electronic Systems Command, Washington, D. C. 20360, October 1969.

Electronic Equipment for Long Time Space Vehicles, Uniformity Project 316-7, A2-260-AEDO-7.

Printed Wire Boards (Copper Clad) Design, Documentation, and Fabrication Of, MSFC-STD-154A, Dec. 15, 1965.

Connectors, Flat Conductor, Flexible Electrical Cable, MSFC-SPEC-219A.

Cable, Flat Conductor, Flexible, Electrical Copper, MSFC-SPEC-220B.

Flat Conductor Cables and Connectors; Data-Standards-Graphs and Other Info., Prototype Development Branch, Astrionics Laboratory, Geo. C. Marshall Space Flight Center, Huntsville, Alabama.

Flat Conductor Cable Technology, NASA SP-5043, 1968, Marshall Space Flight Center, Huntsville, Alabama.

Connector, Electrical, Zero-G, Specification For, 40M39580, April 1, 1969, Geo. C. Marshall Space Flight Center, Huntsville, Alabama.

Flexible Circuits, Wiring, and Cable Design, Construction and Inspection Of, Specification For, MSFC - 50M60150.

Standard Hardware Program, NAVWEPS OD-30355, Design Techniques and Advance Concepts.

Cable, Electrical, Flat Multiconductor, Flexible, Unshielded, MIL-C-55543, 15 November 1968.

Connector, Electrical, Environment Resistant, For Use with Flexible, Flat Conductor Cable, General Spec For, MIL-C-55544, Dec. 26, 1968.

Electronic Module, Aircraft, General Requirements For, MIL-E-19600, Dec. 1, 1965.

Terminal Junction Systems, General Specification For, MIL-T-81714, Mar. 14, 1969.

Wiring Guided Missile, Installation Of, General Specification For, MIL-W-8160D, 24 Dec. 1963.

Maintainability Program Requirements, MIL-STD-470, Mar. 22, 1966.

Adhesive, Epoxy, Electrically Conductive, LSP-14-4011A, Dated 9-20-68, Grumman Aerospace Corp.

Application of Thermally Conductive Interface Material, LSP-14-18051A, Dated 5-29-70, Grumman Aerospace Corp.

APPENDIX

A.1 INVERTERS

The most common types of inverter circuits are as follows:

- Parallel single stage. This produces a square-wave output at the fundamental frequency. This circuit is rich in low even harmonics, and thus requires heavy filtering. It is difficult to provide voltage regulation directly, and a DC pre-regulator is usually used, adding weight and volume and reducing efficiency. These circuits are also difficult to produce with multi-phase outputs with any sort of tight tolerance on the phasing. In three-phase delta-connected versions, for example, large third harmonic circulating currents flow, further distorting the waves, causing additional losses, and making phasing difficult to hold closer than ±5°.

- Quasi-square-wave parallel single stage. This is generally used to eliminate some of the above noted problems in multi-phase circuits. All the other difficulties noted above still hold.

- "Step-wave" or "harmonically neutralized" parallel or bridge multiple stage. This type of circuit solves most of the design problems noted above since it synthesizes a sine wave by summing individual quasi-square-wave stages. Filtering is reduced since the lowest harmonic present is

  $$f_{h\,min} = f_o\,(2n \pm 1), \text{ where } n = \text{number of stages}$$

  The ± factor is load and load power factor dependent, and also depends on the accuracy with which the individual state voltage levels and pulse widths are held. This type of circuit is far less load power factor sensitive than either of the above. Voltage regulation and efficiency are simplified and improved. Pre-regulators are not necessary, although this may lead to slight weight and volume penalties in the filters.

This circuit, however, still has the disadvantage that several power switching stages are required to synthesize the wave. Each stage, while contributing equal volt-amperes, does so at different voltage levels and pulse widths. The result, before filtering, is a stepped-wave with more or less straight sides, which is easily filterable. Inverter weight, however, is in the order of 25-35 lb/Kw.

- Pulse-synthesized bridge single stage. This circuit is the baseline design used in this study. It is the lightest and smallest of all the sine-wave synthesis circuits. It is also the most efficient. The device uses a single bridge stage operating at two frequencies, one a harmonic of the other. The basic power switch is shown in Figure A-1. Waveshapes are shown in Figure A-2. As can be seen, the positive half-cycle is generated by turning "on" (saturating) Q4 and pulse-saturating Q1. The pulses are generated by a reference oscillator operating at, for example, the 12th harmonic of the fundamental (24 pulses per cycle). The volt-time integral under each pulse is equal to that under the equivalent sinusoid. This integral is controlled by low-level logic circuitry which stretches and compresses, as required, each pulse of the harmonic frequency. The harmonic frequency is divided down by other logic to the fundamental, and is used to control the (B) side of the bridge. Thus, during the positive half-cycle, the voltage from (A) to (B) takes the shape noted in Figure A-2 due to the fact that Q4 is turned "on" continuously for the half-cycle, and Q1 is turned "on" and "off" for varying intervals at the harmonic rate. Filter elements L1 and C1 alternately store and release energy to the output, shaping the wave to a sinusoid. This scheme is relatively insensitive to a wide range of load power factors since the voltage regulation loop is part of the pulse-width control.

  It is worth noting that this technique has been independently developed by at least three sources. It was reported at the 1969 IECEC by General Electric in a 1 Kw version. Improved versions have been discussed informally with Dr. Paul Pittman of Westinghouse and Dr. Francis Schwartz of the Lewis Research Center. Additionally, Grumman has an in-house development program to utilize this method with capacitively summed synthesis, which should reduce

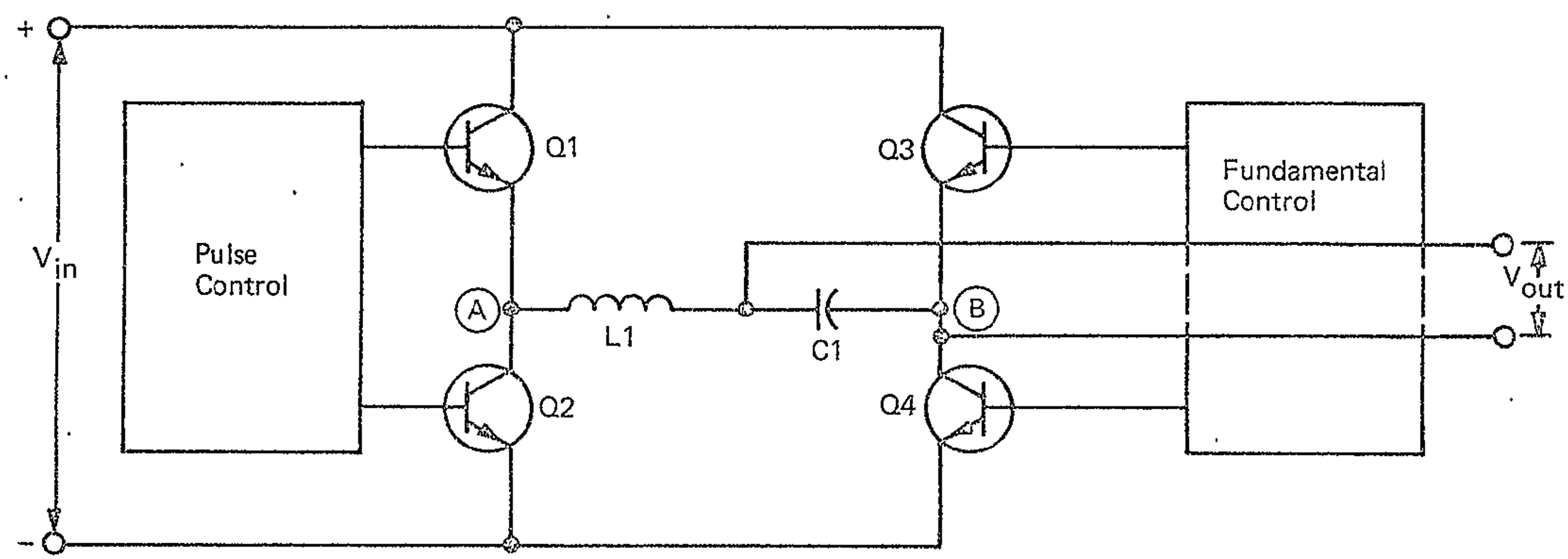


Figure A-1. POWER SWITCH MODULE, SINGLE PHASE INVERTER SCHEMATIC

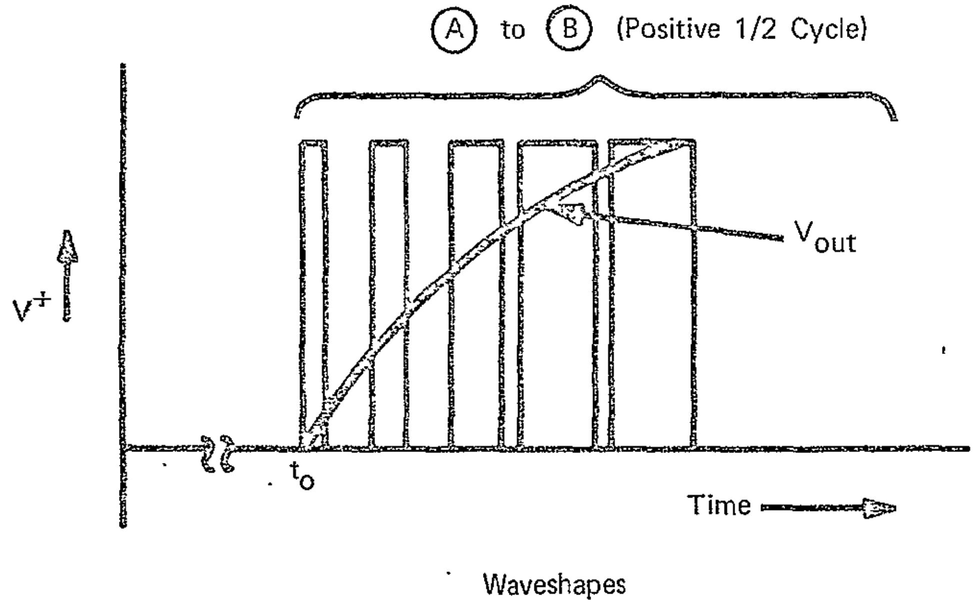


Figure A-2. PULSE SYNTHESIZED INVERTER

weight, volume, and losses (the last by reducing required bias power). The present G.E. configuration delivers 1 Kw at 19.5 lb and 85% efficiency. There seems no reason why weight should not be reduced to 14 lb/Kw and efficiency raised to at least 86-88%.

The performance criteria assumed for this study were as follows:

a) Input Voltage. Any discrete voltage within the following ranges:

28 V ±4 V

56 V ±8 V

112 V ±16 V

b) Output Voltage. 115 V, 1-phase reconnectable to 26 V, 1-phase at full power

c) Output Frequency. 400 Hz

d) Total Harmonic Distortion. 4% maximum (rms)

e) Single Harmonic Distortion. 3% maximum (rms)

f) Voltage Modulation. 4% peak-to-peak under steady state load and input conditions

g) Load Power Factor. 0.7 lead to 0.7 lag

h) Regulation (Static).

   1. Voltage. ± 1% for any combination of 25% to 100% load, any load P.F. within the range, and any input voltage within the range

   2. Frequency. ±0.1% for the conditions stated above

i) Transient Response.

   1. Voltage.

      a. Max. Deviation: 10%

      b. Recovery Time: < 25 msec to within regulation band

c. Conditions (STEP):

(1) Load change from 25% to 100%

(2) Power factor change from 0.7 lead to unity, or to 0.7 lag at any load between 25% and 100%

(3) Input change from minimum to maximum voltage

2. Frequency

a. Max. Deviation: 1%

b. Recovery Time: <10 msec to within regulation band

c. Conditions: Per 1. above.

j) Other Performance Characteristics:

1. Capable of connection with equivalent single-phase assemblies to provide:

a. 115 V, 2-phase (90°) power

b. 115 V/200 V, 3-phase, 4-wire

c. 115 V, 3-phase, delta

d. 26 V equivalent of a. through c. above

2. In any of the above connections, phase rotation shall be selectable by predetermined interconnection of the reference oscillators.

3. In any of the above connections, two or more equivalent assemblies may be parallelled with load sharing and auto-synchronization. Load sharing (current) error shall not exceed 5%. Synchronizing shall be provided by using one oscillator as the master and the rest as slaves. However, the failure of the master shall cause the highest slave to "take-over" with no power interruption exceeding 1 cycle and no frequency transient exceeding 1%.

4. Where paralled connections are used to establish redundancy, the failure of any component or function module shall cause both input and output power to be disconnected from the assembly.

5. Each function module shall contain built-in test equipment (BITE) which shall provide a positive signal if the module fails. For certain modules where degradation may be a problem, the BITE shall provide a signal when and if degradation beyond critical levels occurs.

6. All modules and assemblies shall be designed to be self-protecting against input or output transients and/or overloads or short circuits. While the existence of such fault conditions may cause temporary out-of-spec performance, no permanent damage shall result from such faults. Removal of the fault conditions shall restore normal performance.

7. Remote sensing capability shall be a design feature (for voltage regulation).

8. Coordination of protection against shorts and overloads shall be made with the circuit interruption devices used in the power distribution and management system. BITE signal data transmission for display and maintenance purposes shall be coordinated with the On-Board Checkout (OBC), power distribution, controls and displays, and data management subsystems.

9. Designs will be consistent with the requirements of MIL-1-6181D, or subsequent revision, unless otherwise specified.

A.2 DC-DC CONVERTER/REGULATORS

In both of the non-isolated switching converter/regulators shown in Figure 6-12, Q1 acts as a switch, turning on/off at a specified repetition rate. In the bucking unit of Figure 6-12a, L1, CR1, and C1 act as an input filter, smoothing the current drain at the input. When Q1 is "on", the input voltage appears at point A, and current starts to increase through choke L2, charging C2. When Q1 turns "off", the current through L2

Q1: $I_{in} \cdot V_{sat}$ + Switching Loss + Base Loss

CR2: $(I_{load} + I_{charge\ (C2)})\ V_F$ + Switching loss

L1: $I_{in}^2\ R_{L1}$

L2: $I_{load}^2\ R_{L2}$

C1: $\dfrac{(V_{in} + \Delta V_{in})^2}{ESR_{C1}}$, ESR = Equivalent Series Resistance

C2: $\dfrac{(V_{out} + \Delta V_{out})^2}{ESR_{C2}}$

CR1: $\dfrac{\Delta I_{in}}{D}\ V_{F(CR1)}$

The last three items are nearly negligible, contributing less than 1 percentage point to the total loss for any reasonable component selection criteria. The choke losses contribute between 1.5 and 2 percentage points total. The balance of the losses are all to be found in Q1 and CR2, and are approximately equally split except for the base power. For any reasonable switching rate, the following criteria are of prime importance:

a) The switching times of Q1 (t_r, t_f and t_{stg}) must be small. Typically, for a 10 KHz repetition rate, $t_r \leq 200$ nsec, $t_f \leq 500$ nsec, and $t_{stg} \leq 500$ nsec would be mandatory at the operating condition.

b) The base drive must be adequate to force the transistor into saturation, but not so high that the minority carrier swap-out time becomes a problem. The usual circuit is designed for a base drive of 2-3 times that required by the minimum low-temperature current gain.

c) The switching times of CR2 are critical. In particular, if the diode is unable to recover its blocking capability before Q1 turns completely on, it can see very high current pulses at relatively high voltages. Thus, for CR1 recovery,

$$t_{stg} + t_r \leq t_{r(Q1)}$$

d) C2 should have low ESR and low ESL, as these add to the CR2 losses considerably. (ESL is the Equivalent Series Inductance.)

With today's state-of-the-art, 10 KHz converters with $\eta \geq 94\%$ are quite practical. Similar criteria and design equations can be worked out for the boost circuit. Here:

$$\frac{V_{out}}{V_{in}} = \frac{1}{D} \tag{6}$$

$$\frac{I_{load}}{I_{in}} = \eta D \tag{7}$$

With care in selection of the components, $\eta \geq 92\%$ at 10 KHz is practical. Specification criteria for this type of equipment follows the general pattern of the inverter in terms of items a), i) 1a, i) 1b, i) 1c (1) and (3), j) 3 (load sharing), and j) 4 through 9. Other performance characteristics are as follows:

a) Max. buck output voltage $= V_{in} - \left(I_{in} R_{L1} + V_{sat\ (Q1)}\right) = I_{load} R_{L2}$

b) Min. boost output voltage $= \frac{V_{in}}{D} - V_{F(CR1)}$ (at $I = I_{load}$)

c) Regulation (static): ±0.25% for any combination of load from 10% to 100% and any input voltage within the range

d) Weight: approximately 7 lb/Kw